RADIO DIRECTION FINDING
10 kc-s to 550kc-s
Walter C. Weaver

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by

Walter C. Weaver

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
ENGINEERING ELECTRONICS

United States Naval Postgraduate School
Monterey, California

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ABSTRACT

This paper reviews the problems involved in the location of a non-cooperative transmitter in the 10 kc/s to 550 kc/s range. The information is presented in simplified form for easier understanding by non-technical personnel. Formulas and references are given for the engineer's use. The paper covers propagation characteristics, theoretical methods of radio location, and practical radio direction finder systems now in use or that may be used. An evaluation of the advantages and disadvantages of most of the practical systems is given.

FORWARD

The purpose of this paper is to present the problems involved in locating a non-cooperative transmitter that is transmitting in the frequency range from 10 kc/s to 550 kc/s. It is intended that the material be presented such that a non-technical person may grasp the ideas involved in radio direction finding, yet at the same time, to present sufficient theory and references that the engineer may continue into the problem.

Radio direction finding is as old as radio itself. It has been used primarily for navigation and for the location of non-cooperative transmitters. Between World Wars I and II there was a great concentration of effort on the use of frequencies above 1500 kc/s and as a consequence, most of the work on radio direction finding was done on the higher frequencies. The advent of World War II brought a renewed interest in the use of the very low and the low frequencies, especially in the field of navigation signals. It is because of this renewed interest in the lower frequencies that this paper is written.

The writer wishes to express his appreciation for the assistance and encouragement given to him in this investigation by Professors John Downing and Donald Stentz of the Department of Electronics of the United States Naval Postgraduate School and to Messrs. Henry Blanchard and
Priedigkeit
John Preidqkiet of the Radio Systems Laboratory of Stanford Research Institute at Menlo Park, California.

SYMBOLS AND ABBREVIATIONS

θ = Angle of arrival in azimuth (in radians unless otherwise noted)

e = Voltage induced in an antenna

N = Number of turns in a loop

A = Area

$\overline{E}$ = Field strength in micro-volts/meter

λ = Wave length of signal

w = radians

he = Effective height of an antenna

f = Frequency

c = Velocity of propagation (usually approximated to 3×10^8 meters per second)

L = Inductance in henries

r = Radius

a = Radius of conductors or a bundle of conductors taken as a unit

Rr = Radiation resistance

R = Resistance (ohmic)

Z = Impedance

$\mu = 4\pi \times 10^{-7} = 1.257 \times 10^{-6}$ henries/meter

d = Distance (generally separation of two antennas)

t = Time or time difference

ϕ = phase difference

Δ = an incremental change (this is a prefix)

I = Current

E = Voltage

ln = Natural log (base ϵ)

k = 1.38×10^{-23} joules/degree Kelvin Boltzmann's constant)

$u = 10^{-6}$

uv/m = micro-volts per meter

Δf = bandwidth

En = noise voltage

f_o = frequency to which the circuit is tuned

α = angle of arrival in elevation

h' = apparent height

d' = apparent distance

$\simeq$ = approximately

f_d = peak frequency deviation if an infinite number of antennas were used

f_r = rotational frequency of the antenna

A_m = minimum number of antennas for a maximum $\pi/2$ radians phase shift between antennas

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CHAPTER I

COMMUNICATION AND PROPAGATION

1.1 Communication at the Lower Frequencies.

The basic uses of radio transmissions are to convey intelligence or to produce an action. It seems reasonable to state that the lower frequencies are used to convey intelligence over ranges greater than 50 miles since more satisfactory means are available for the shorter ranges. There are, as in most things, a few exceptions to this statement.

The advantages of using the lower frequencies for communications lies in the fact that these frequencies are less affected by ionospheric disturbances, and reliable coverage of very large areas is obtainable. The ground wave propagation is of major importance on the lower frequencies whereas it is of negligible value at frequencies much over 1500 kc/s. The use of the ground wave permits very accurate navigation systems and hence we may expect to find numerous navigational transmission on the lower frequencies. The reliable, large area coverage results in the use of the lower frequencies for "fleet" type coverage such as is used by the United States Navy and for long range navigational systems.

The disadvantages of using the lower frequencies lies in the limited bandwidth available and the fact that very high powered transmitters are required due to low antenna efficiency. For this reason it is not expected that there will be many long range mobile transmitters in the frequency range below 400 kc/s.

The types of transmissions that might be found at the lower frequencies may be broken down in the following catagories:

a. Navigational signals

b. Written messages

c. Spoken messages

d. Pictorial messages

f. Miscellaneous transmissions

1.2 Navigational Signals.

Navigational signals encountered in this frequency range are either of the long time base or the short time base systems. The long time base systems employ a carrier which is on continously for a long period of time and which may or may not be modulated. This type signal is used for navigation by direction finder techniques, phase comparison, or amplitude comparison methods. This system is characterized by the very narrow bandwidth required for the signal and the likelihood that there will be only one transmitter on a given frequency.

The short time base systems are characterized by the fact that the signal transmitted by any one transmitter is relatively short and that there is generally more than one transmitter sharing the same frequency. These systems usually work on time differences, phase comparison, or amplitude comparison techniques. In this type of system the transmitter may be on for only a very short period of the cycle time. It is these systems which will probably pose the greatest problem for a radio direction finder network.

1.3 Written Messages.

Written messages will probably be the most prevalent type of emission found on the lower frequencies. Such messages are generally sent in either Morse code or in teletype code. Morse and teletype codes are both basically an "ON-OFF" (or binary) system, that is, the operator or

the equipment detect information from the combinations of the presence of a signal and the lack of the signal. Such "ON-OFF" codes may be transmitted by several methods.

The method most used at the present for transmitting written messages at the lower frequencies is the "CW" (or A-1) method where the carrier is either "ON" or "OFF" to represent the two conditions. This system has the advantage that all of the radiated power goes into the intelligence and the bandwidth is very narrow. The major disadvantages of this system are that automatic volume control is difficult and the system does not lend itself ideally to automatic printer operation.

Another method of transmitting binary code is by the use of a continuous carrier and tone modulation (A-2). In this case the presence of the tone might indicate the "ON" condition and the lack of a tone might indicate the "OFF" condition. A variation of this method is to use two tones, one to indicate the "ON" and the other to indicate the "OFF" condition. This system might be multiplexed (putting more than one channel of information on a single transmitter) by using several pairs of tones, each pair representing one channel of intelligence. The advantages of this system are that automatic volume control can be used and the signal is relatively easy to "tune in" on a standard receiver. The disadvantages are that less than one-half of the radiated power goes into the intelligence, the remainder of the power being in the carrier. It is of course possible to transmit this signal without the carrier in which case it becomes a suppressed carrier system. When this is done, it is also normal to suppress one side band of the signal (thus reducing bandwidth) and this type of signal is called a "single side band, suppressed carrier system". This type of signal has several very good advantages which make

it a very desirable system and one which will probably be used in the future to a large extent. It has the disadvantage in that the transmission and receiving equipment are fairly complex.

Frequency shift keying has been a popular method to transmit Morse and teletype signals. Frequency shift keying (FSK) is best described by saying that two carrier frequencies very near each other are used to indicate the two conditions. In practice the transmitter is merely shifted between the two frequencies. This system has the advantage of putting all of the power into the intelligence. Automatic volume control may be used and the system is very good for automatic printer operation. The bandwidth required for this system is much less than that required for a voice transmission. The transmitting and receiver equipment are relatively simple. Multiplexing by frequency shift methods for two channels of intelligence is possible by shifting between four frequencies instead of two frequencies. Three channels of intelligence are obtainable by shifting between eight frequencies. It is not likely that more than two channels of intelligence will be transmitted by this method due to the increase in bandwidth for the higher number of channels.

1.4 Spoken Messages.

Spoken messages are used when:

a. Direct contact between the two interested parties is desired.

b. Rapid communications is desired.

c. Minimum operator training is desired.

d. Near minimum equipment is desired.

This type of emission is always likely to be popular. It is not used to a great extent below 400 kc/s, however, due to the wide bandwidth required. Normal double side-band amplitude modulation requires at least

a seven kc/s bandwidth for good intelligibility. In the frequency range of interest the spoken message will probably be transmitted as a double side-band, non-suppressed carrier (A-3). A single side-band, suppressed carrier may be used. Wide band FM will probably not be used in this frequency range.

1.5 Pictorial Messages.

Pictorial messages or photofax is sent either as amplitude modulation or frequency modulation. Due to bandwidth limitations only still pictures are apt to be sent on the lower frequencies since television requires too great a bandwidth for use on these frequencies. A simple FSK or "ON-OFF" tone modulation could be used for a picture that has no "shades". When "shades" (degrees of gray) are desired the signal is generally sent via some form of narrow band FM or AM with the subcarrier frequency modulated. Direct amplitude modulation is seldom used for this purpose. Pictorial pictures may be sent with narrow bandwidths (300 cps or less) provided that the time for transmission is made relatively long per unit picture area.

1.6 Miscellaneous Transmissions.

The category of miscellaneous transmissions is included to cover transmissions used for remote control (such as ships and aircraft) and uses in which the radio emission is an undesired by-product (such as industrial heating, man made noise, and the like). In may be very important to locate these signals by direction finding when such signals interfere with communications.

1.7 Problems of Transmission.

Once the problem of what is to be transmitted is solved, the matter of how to transmit it becomes of importance. There are two major points

that come into the problem of how to transmit the desired signal and they are "Noise" and "Interference". If it were not for noise the choice of power would not be important since only a small amount of power would be required and the choice of frequency would be based only on interference.

Noise, for the purposes of this paper, may be divided into three classes:

a. Internal receiver noise

b. Antenna noise

c. Atmospheric noise.

A complete analysis of noise is well beyond the intention of this paper since this subject alone could occupy more pages than this thesis is composed. For purposes of this paper several assumptions will be made in regards to noise. They are that:

a. Noise voltage is additive by adding the squares of each noise voltage and then taking the square root of this sum.

b. Noise power is evenly distributed when considered over a narrow band of frequencies.

c. Noise voltage is proportional to the square root of the bandwidth (the noise voltage is doubled when the bandwidth is increased four times).

For more information on noise, refer to references (1) and (2) in the bibliography.

1.8 Receiver Noise.

It will be sufficient to say that the receiver noise is roughly equivalent to 0.1 microvolts at the input terminals (low impedance such as 50 ohms) for a good receiver in the frequency range under discussion

when the receiver is on the narrow bandwidth position (about 200 cps).

1.9 Antenna Noise.

Antenna noise is due to the antenna ohmic resistance and to the antenna radiation resistance. Since many antennas have an impedance different from that desired for matching purposes, a matching device must be used to couple the antenna to the transmission line or to the receiver. In many cases this coupling device has considerable effect on the overall antenna noise. It will be desirable in this paper to discuss the antenna noise as the noise from the antenna system present at the input to the receiver. One method of evaluating antenna noise is to determine the required signal strength in micro-volts per meter (uv/m) at the antenna required to give the same imput to the receiver in micro-volts as the noise from the antenna system in micro-volts. This value is known as the "Equivalent noise signal.(Eqn)". This value takesinto account both the effective height (he) of the antenna, and the antenna system noise.

1.10 Atmospheric Noise.

Atmospheric noise is basically due to thunderstorms throughout the world. Its characteristics are sharp random spikes of noise on a background of random noise. Other external noises which are present include cosmic noise and man-made noise. The latter two are not discussed in this paper since the atmospheric noise is generally the predominant noise at the lower frequencies. Atmospheric noise is generally measured in root-mean-square (rms) micro-volts per meter for a given bandwidth (generally either 400 cps or 1000 cps bandwidth).

Atmospheric noise is predictable to an extent (3). Figure 1.1 shows a prediction of radio noise for part of the United States on the

basis of rms noise level vs. frequency. Figure 1.2 shows measured summer noise at one location in the United States on the basis of time of day and frequency. From these figures and other information the following general statements may be made about atmospheric noise in the 10-550 kc/s band:

a. Atmospheric noise is highest at the lower frequencies

b. Atmospheric noise is higher during the night than during the day

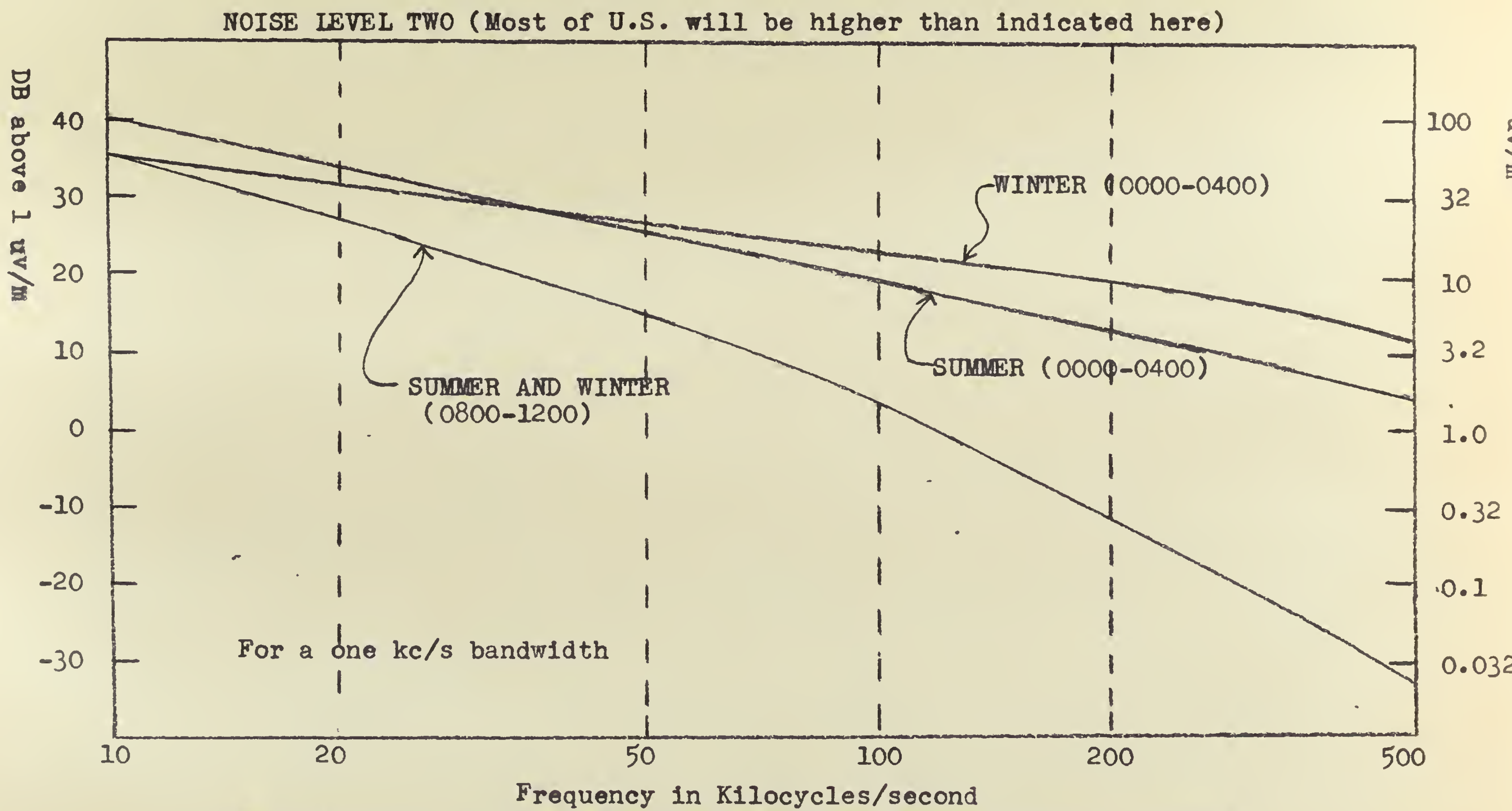
c. Atmospheric noise is higher near the equator and decreases towards the poles.

In the design of an antenna-receiver system it would be ideal if the noise at the receiver were predominantly atmospheric noise. This would mean that the antenna and receiver noise would not have to be considered. It should also be noted that the receiver bandwidth should be ideally only as wide as required to pass the signal. Any greater bandwidth will only increase the noise level without increasing the signal level.

1.11 Radiated Power and Signal Strength.

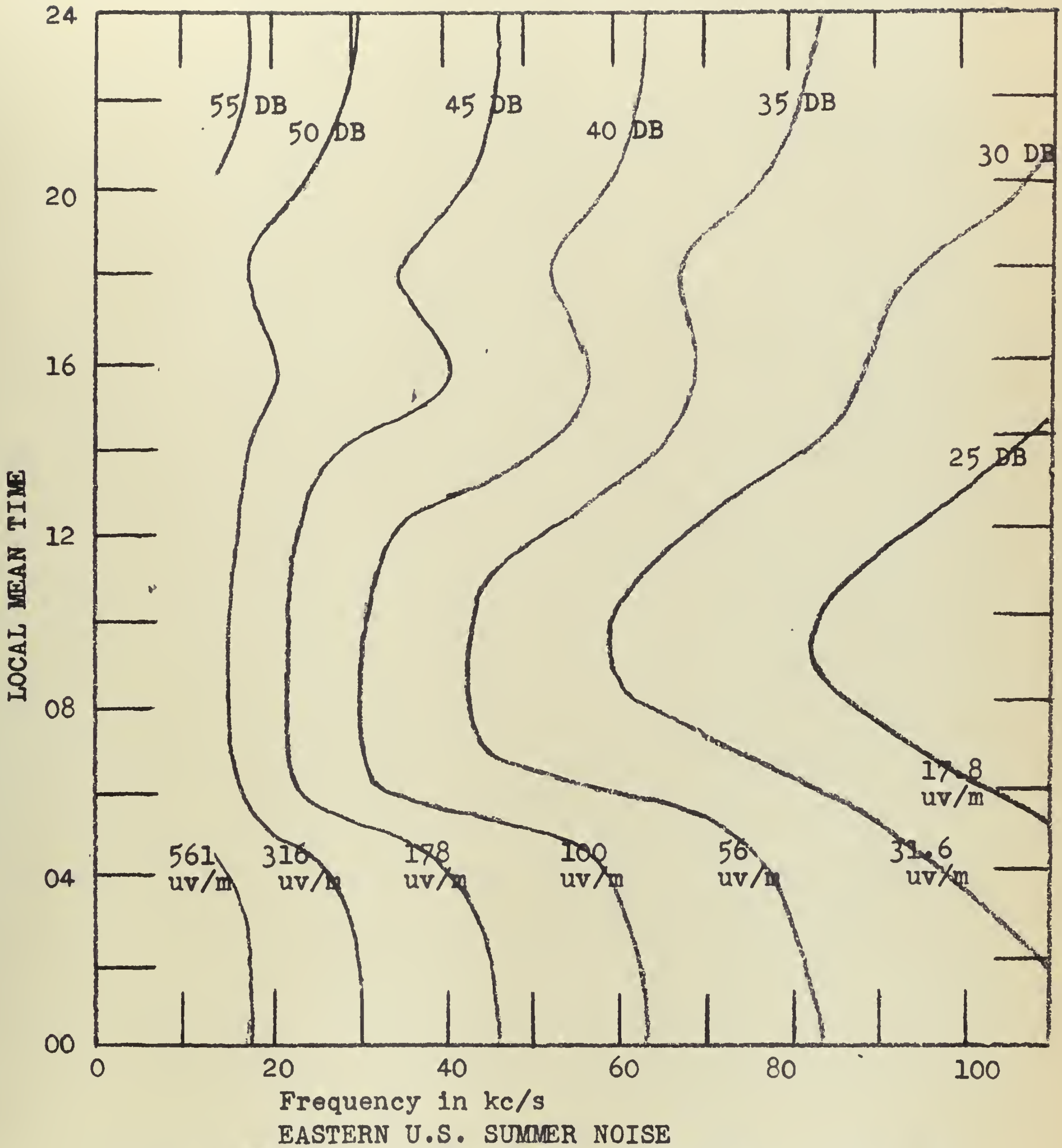
It will be sufficient to say, for the purpose of this paper, that the actual radiated power to the power generated by the transmitter (antenna efficiency) is relatively low in the band under consideration. It becomes increasingly difficult to obtain good antenna efficiencies as the frequency decreases, since antenna efficiency falls off as the height of the antenna becomes small with respect to the wave length.

The actual radiated power is only part of the question. The major part of the question is how much of the radiated power appears at the receiver site. The factors involved in the transmission of the signal



MEDIAN VALUES OF RADIO NOISE EXPECTED FOR A SHORT VERTICAL ANTENNA
(National Bureau of Standards NBS 557)

Figure 1.1



EASTERN U.S. SUMMER NOISE

Contours of constant RMS atmospheric noise, in uv/m and in DB above one uv/m for a 400 cps bandwidth for the months of July and August 1951

(CRUFT LABORATORY Technical Report No. 158)

Figure 1.2

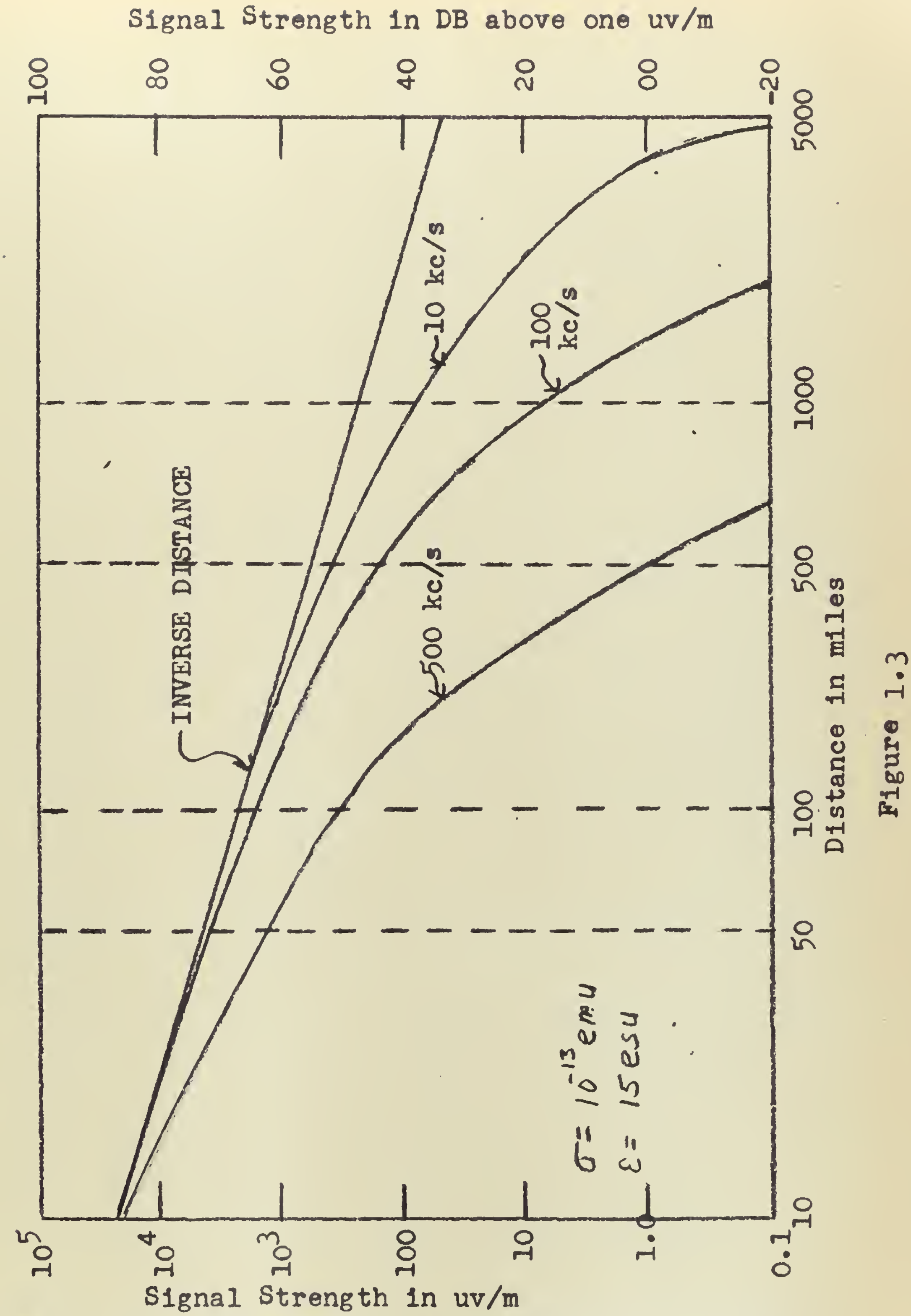
from the transmitting antenna to the receiving antenna are discussed under the general heading of "Propagation". There are two important paths or routes by which the transmitted signal may travel to the receiver site. These paths are referred to as transmission by the "ground wave" and by the "sky wave". The "direct" path is not discussed as this is a relatively short range phenomenon.

1.12 Ground Wave Propagation.

Ground wave propagation is entirely by vertically polarized waves (the type of emission from a vertical antenna). Any horizontally polarized radio wave is rapidly attenuated by the earth. For this reason most of the signals propagated in this frequency range are of the vertically polarized type.

Figure 1.3 shows signal strength vs. distance for several frequencies with ground wave propagation over a fair land. The signal strength does not fall off as rapidly as this over water, but may fall off more rapidly over poor land. It should be noted from this figure that the lower frequencies are better for long range ground wave transmission if the radiated powers were the same. An increase in radiated power of four times the power shown would result in doubling the signal strength. The velocity of transmission over water is generally slightly higher than that over land. This difference in attenuation and velocity become important in radio direction finding as will be shown later.

Ground wave propagaion is not particularly dependent on the time of day or the season and hence is very reliable up to the point where the sky wave can begin to interfere with it. On certain types of emissions (pulse type navigational signals and certain time difference direction finders) the fact that the ground wave arrives ahead of the sky wave may be very important.



SURFACE WAVE FIELD INTENSITY FOR A RADIATED FIELD INTENSITY OF 186,400 UV/M AT ONE MILE.
(Stanford Research Institute)

Figure 1.3

It is important to note that the ground wave does not necessarily arrive at the receiving site from the great circle direction of the transmitter. This difference in direction will produce an error which at short ranges or near boundaries between large bodies of water and land can be of a large magnitude and which no built-in degree of accuracy in a direction finder can compensate.

For more information on ground wave propagation see (4) and (5) in the bibliography.

1.13 Sky Wave Propagation.

The sky wave becomes of major importance at night and over long distances. It is not so easy to predict as is the ground wave nor is it as stable. In talking about the sky wave it is normal to discuss the sky wave as being a reflection from a solid sheet located a given distance above the earth. While this is not actually true, it does provide some accurate answers. The height of this reflecting layer is generally known as the "apparent height".

The ionosphere does not reflect all of the power impinging upon it. Much of the power continues on into space or is absorbed. The ratio of the power reflected to the power impinging on the ionosphere is called the "reflection coefficient". The polarization of the reflected wave is not necessarily the same as the incident wave. If we assume that the incident wave is vertically polarized, then the ratio of horizontal polarization to vertical polarization in the reflected wave is known as the "conversion coefficient." The reflected wave may be linearly polarized from vertical to horizontal or it may be elliptically polarized (the polarization rotates) depending on the conversion coefficient and the relative phase between the horizontal and vertical components in

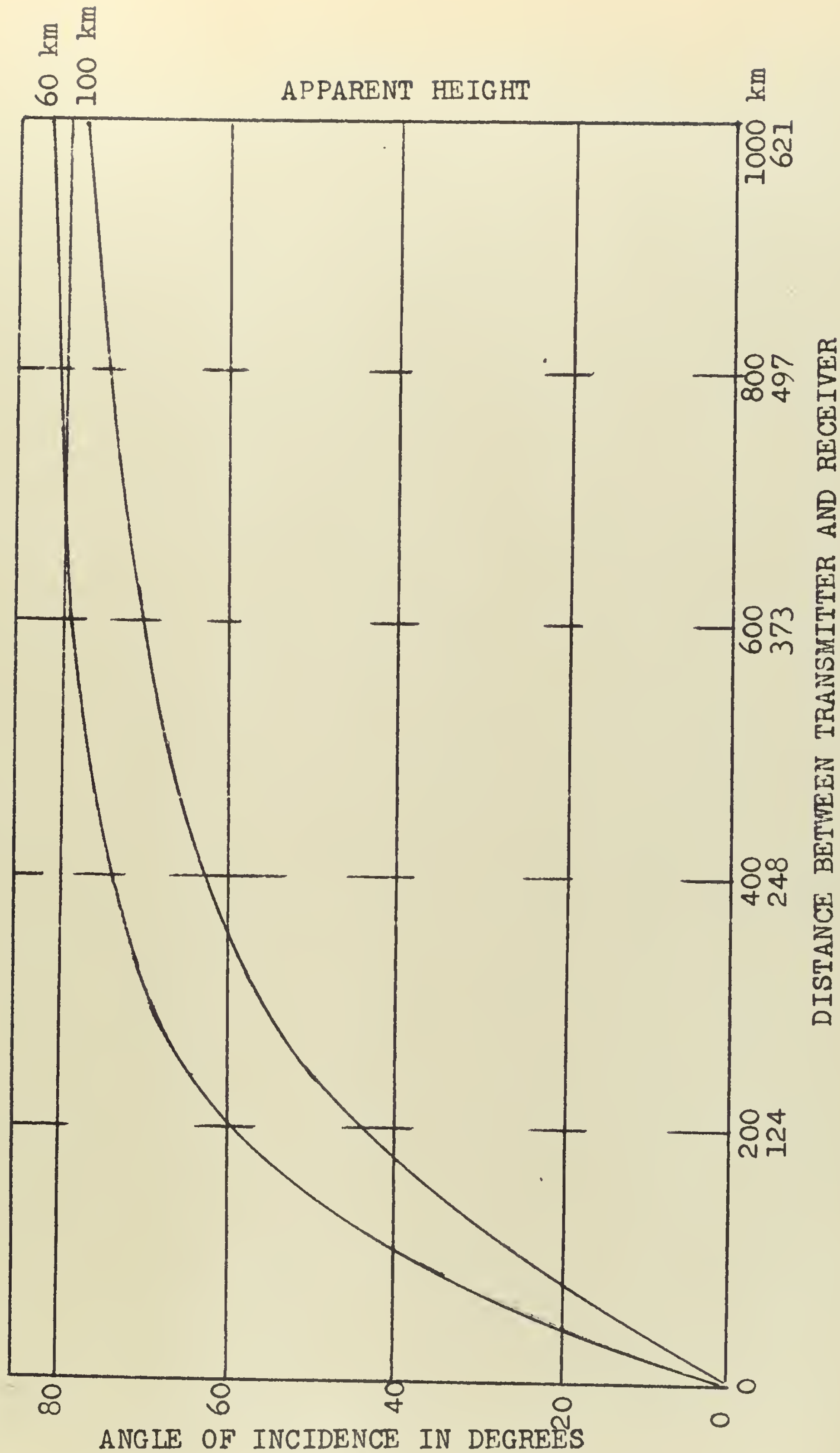
the reflected wave. The reflected wave has been measured (7) to be linearly polarized for the longer ranges and elliptically polarized for the shorter ranges (below 250 miles at 16 kc/s). It should be noted that the reflected wave is not necessarily in phase or 180 degrees out of phase with the incident wave.

Experimental evidence (7) indicated that the apparent height during the day is approximately 45 miles and during the night is approximately 59 miles. There is some evidence that more than one apparent height at a time exists even for these low frequencies.

The reflection coefficient varies greatly. It is normally greater for the lower frequencies in the band under consideration than it is for the higher frequencies, it is generally greater during the night than during the day, and greater as the incident wave approaches tangency with the plane of the reflecting layer (longer hops).

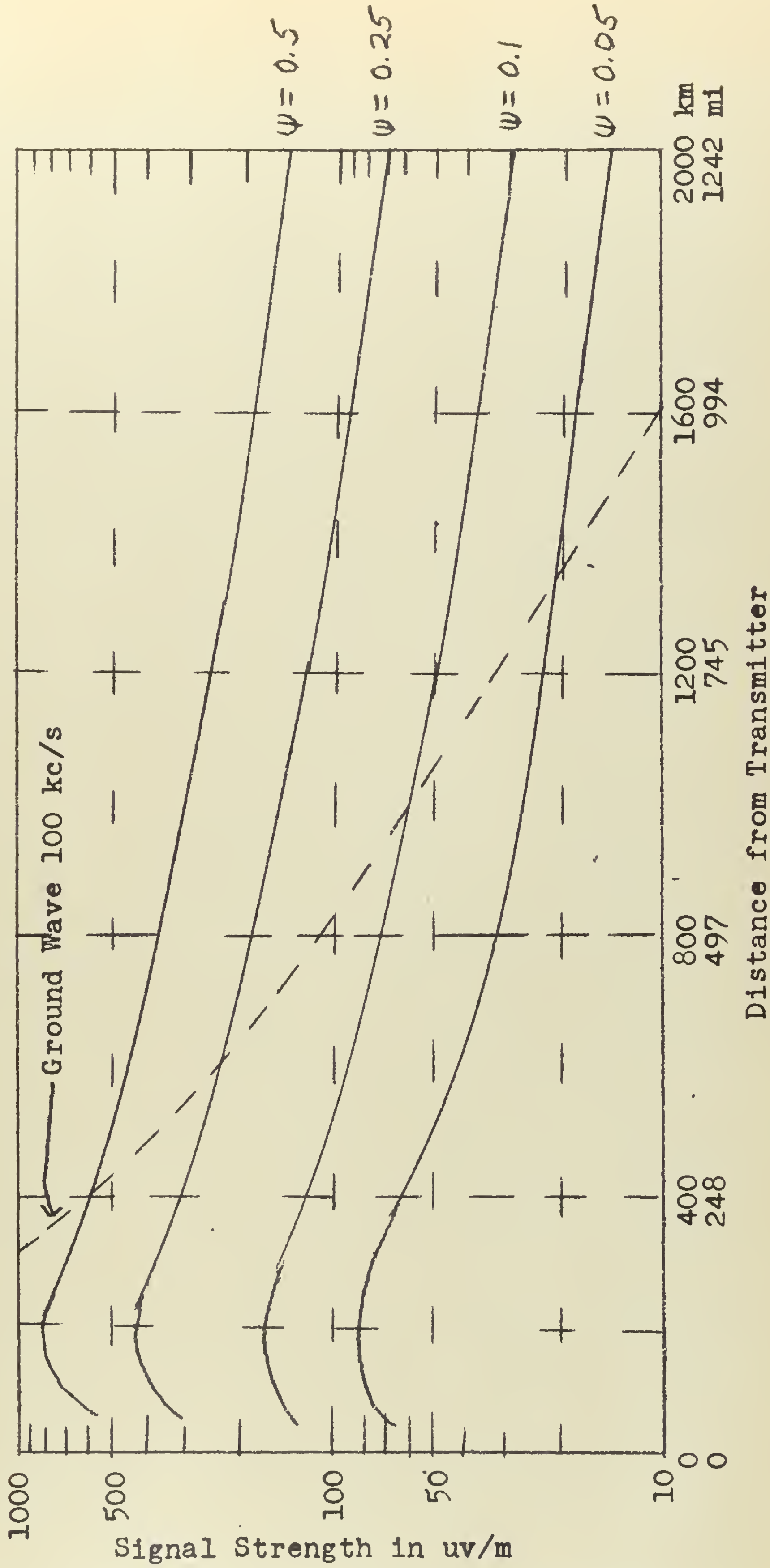
A feature which may be of important in direction finding is the angle of reflection vs. distance for various apparent heights based on the assumption that the angle of reflection is equal to the angle of incidence (see Figure 1.4). The angle of reflection equal to an angle of arrival of zero degrees at the receiving end is approximately 84 degrees for an effective height of 95 km. This gives a one hop transmission a distance of about 800 miles.

Figure 1.5 shows signal strength of the sky wave vs. distance for several different reflection coefficients. It should be noted that the signal strength of the sky wave does not decrease with range so fast as does the signal strength of the ground wave.



ANGLE OF INCIDENCE VS DISTANCE FOR A CURVED EARTH

Figure 1.4



SIGNAL STRENGTH VS DISTANCE FOR SKY WAVE TRANSMITTED OVER A SEA PATH FOR ONE KW OF RADIATED POWER
(IEE Part III March 1951 page 82)

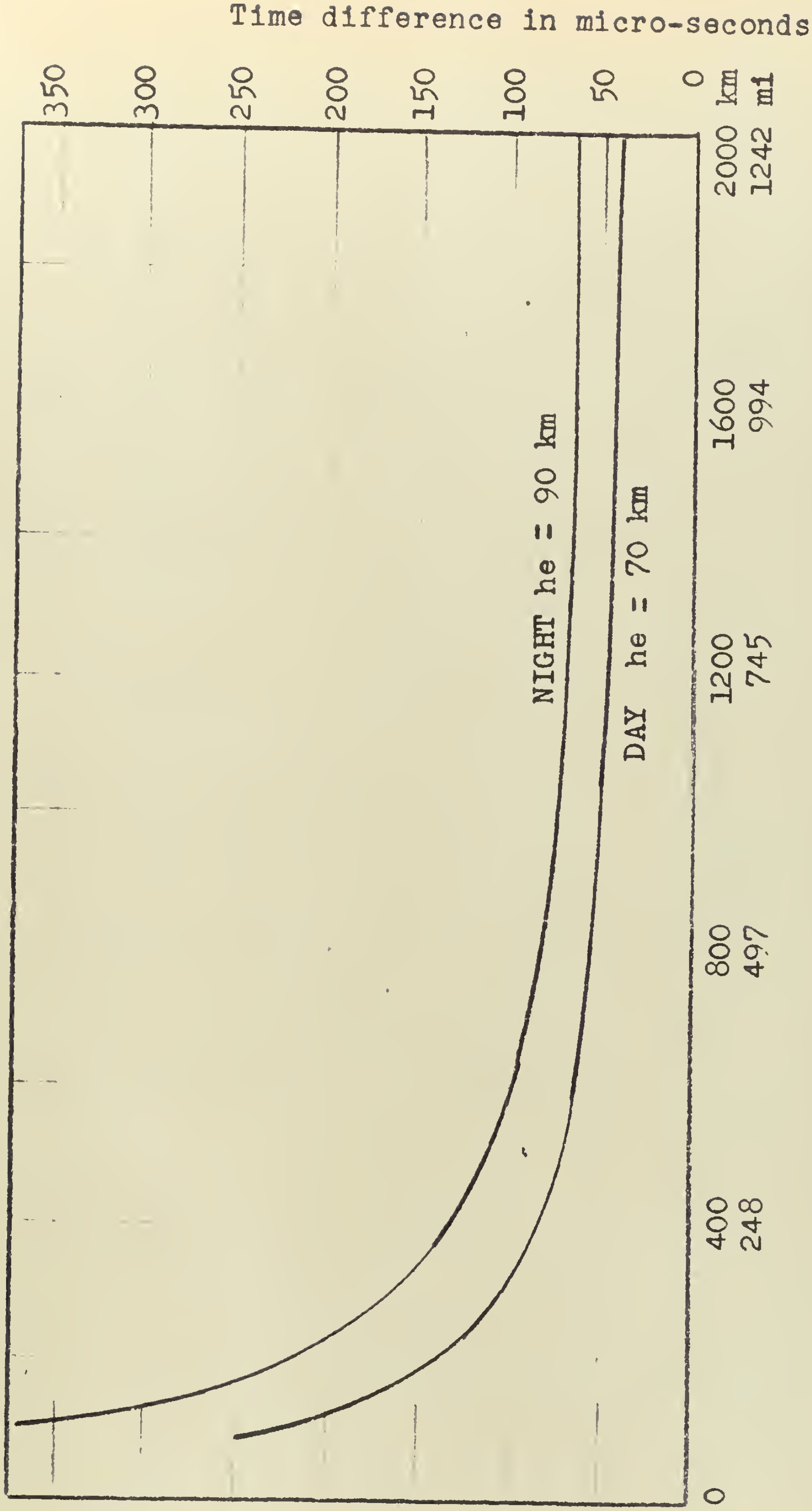
Figure 1.5

1.14 Propagation by a Combination of Ground and Sky Waves.

The arrival of a ground wave and one or more sky waves at a site may cause constructive or destructive addition. The resulting polarity of the signal may be anything from vertically polarized to elliptically polarized. The type of polarization and strength of the signal depends on the strength of the ground and sky waves, their relative phase, the angle of arrival of the sky wave, the relative bearing (azimuth direction of arrival) of the two waves, and the polarity of the sky wave (it being assumed that the ground wave will be vertically polarized).

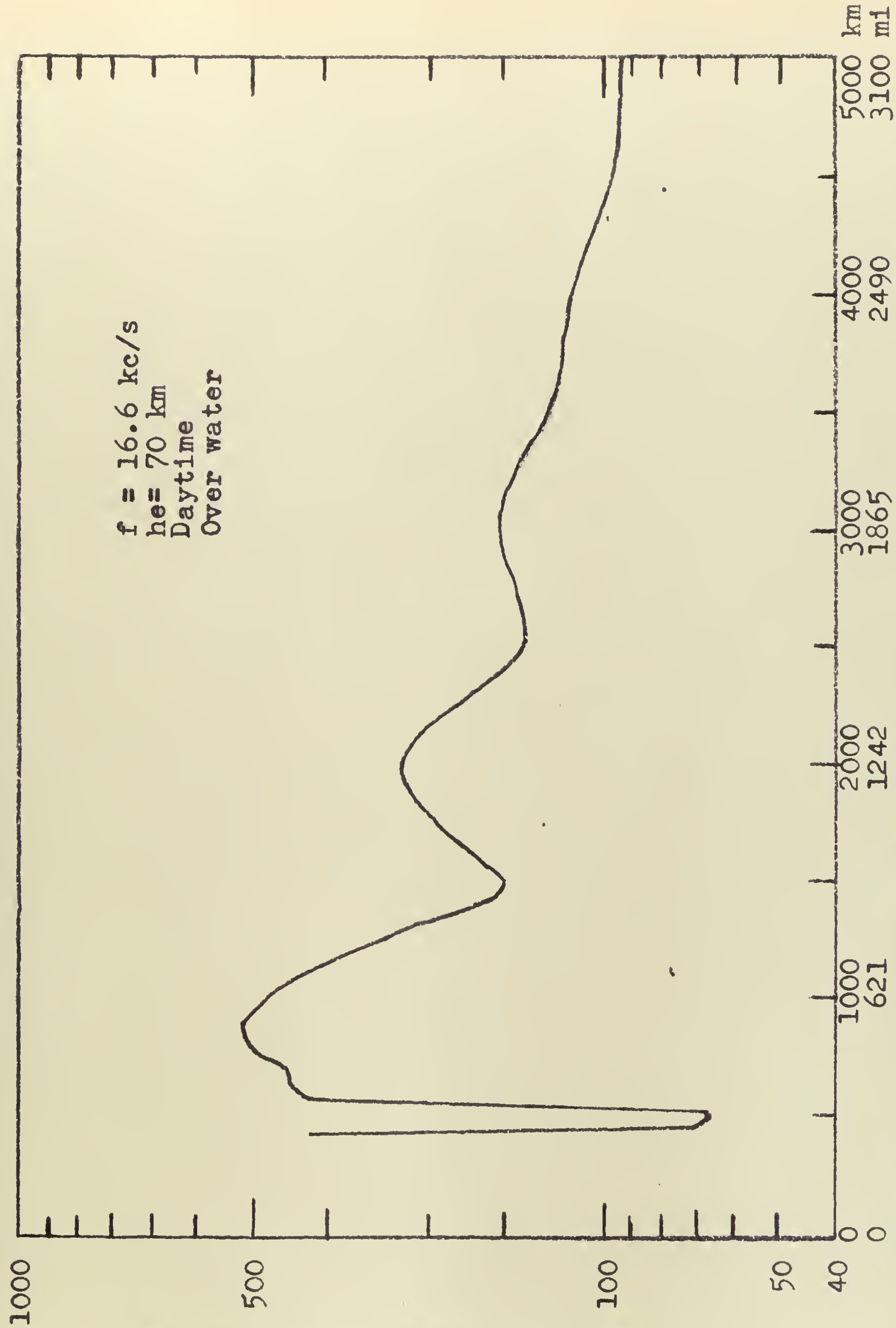
Figure 1.6 is a plot of the time difference of arrival at the receiving site between the ground wave and a one hop sky wave. This difference in time is one of the factors in producing a difference in phase at the receiving site. The other major cause for the phase difference is the phase shift caused during the reflection. Occasionally two waves will arrive at the receiver which are much further separated in time of arrival than those indicated. This effect may be produced by the signal arriving at the receiver from opposite directions around the world. It is of course, also possible for two sky waves that have arrived by a different number of "hops" at the receiver to arrive with a time difference. The one with the least hops would be expected to arrive first.

There has been quite a bit of work done in the field of attempting to predict the field strength for any given frequency, path, and time vs. distance and radiated power. No attempt to go into detail will be given here. The Austin-Cohen equation will be found elsewhere in this paper. See reference (24) of the bibliography. Figure 1.7 shows field strength vs. distance for a given transmitter and frequency at approximately the



TIME DIFFERENCE BETWEEN THE GROUND WAVE AND THE FIRST IONOSPHERE-REFLECTED WAVE PROPAGATED OVER A SPHERICAL EARTH (I.E.E. Part III March 1951)

Figure 1.6



COMBINED GROUND AND SKY WAVE FIELD STRENGTH PATTERN VS DISTANCE
(National Bureau of Standards Report NBS 5022)

Figure 1.7

SIGNAL STRENGTH IN MICRO-VOLTS/METER

Figure 1.7

same time. This figure shows very clearly the reinforcement and cancellation produced by the sky wave arriving in and out of phase with the ground wave. It should be noted that near the transmitter the ground wave is predominant and hence the dips are not so great. At a certain point the ground and sky waves are almost of equal strength and the dips in field strength are quite deep. As the distance increases the ground wave decreases in strength faster than the sky wave, hence the dips gradually decrease in size. The important thing to note here is how soon the sky wave becomes an appreciable part of the signal. This is important because the errors of most direction finder systems are greatly dependent on the sky wave.

CHAPTER II

METHODS OF RADIO DIRECTION FINDING

2.1 Theoretical Methods of Radio Direction Finding.

In this paper, direction finding is defined as a means of obtaining a line of position of a transmitter from the direction finder site. This line of position may be a line of bearing, a line of range, or a line of some other function. In order to locate a transmitter it requires the intersection of at least two lines of position, preferably at right angles. A single station could fill this requirement if the station coudl give both a bearing and a range similiar to a radar "fix". All of the known direction finder systems that are in operational use give bearings only. There are some experimental equipments which give a range.

2.2 Methods of Obtaining a Line of Bearing.

The methods that might be used for obtaining a line of bearing are:

a. A highly directional antenna

*b. Comparison of phase and/or amplitude of two directional antennas

*c. Sharp null type antenna systems

*d. Time difference measurements

*e. Doppler effect.

2.3 Methods for Obtaining a Line of Range.

The methods that might be used for obtaining a line or range are:

a. Signal strength measurements

b. The angle of arrival of the sky wave

c. Time difference of arrival of the ground wave and the sky wave

d. Round the world time difference

e. Relative phase of the sky and ground waves

The (*) indicates what may prove to be the most practical primary systems.

2.4 Highly Directional Antennas.

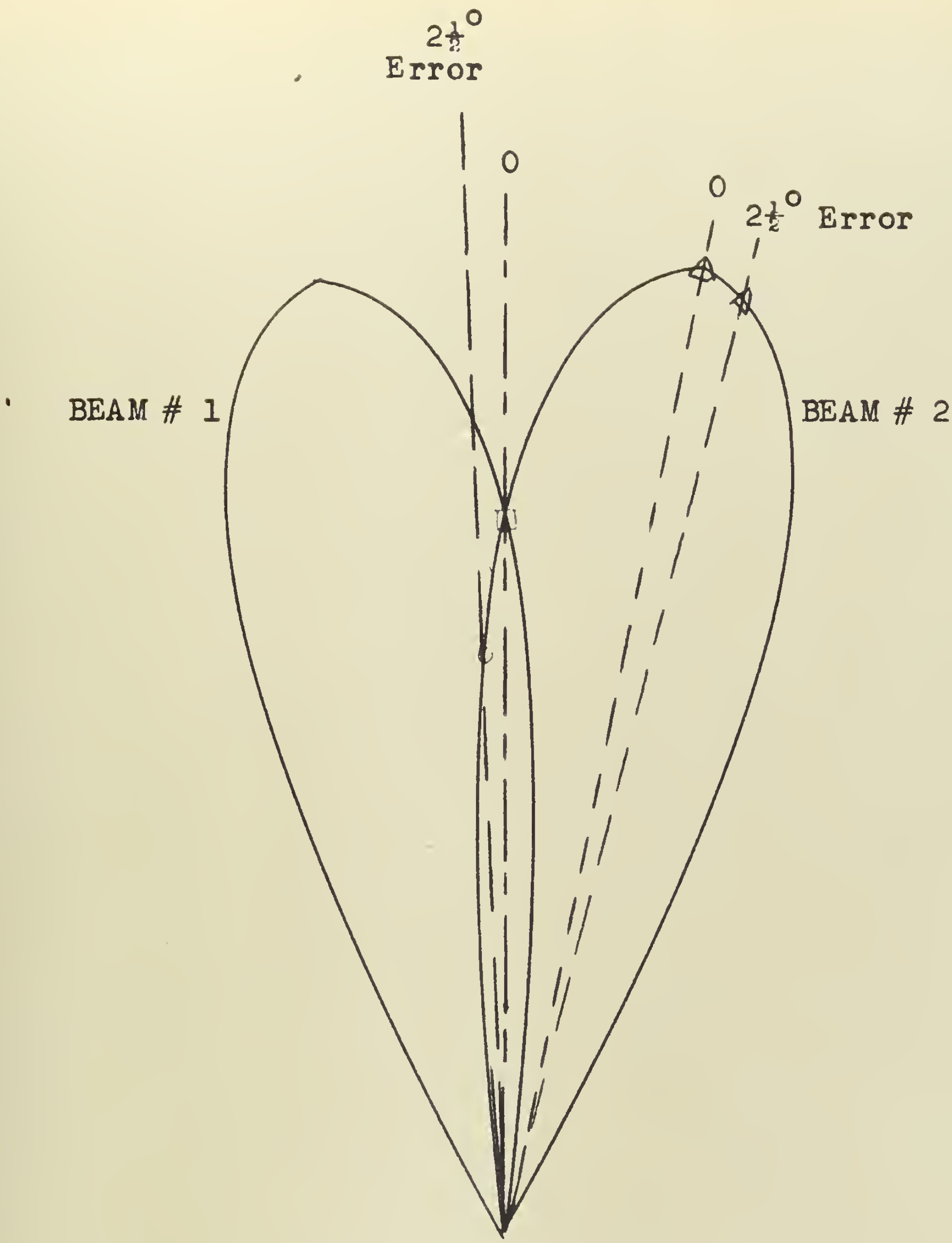
A single antenna at these low frequencies which would have a maximum lobe sharp enough for a direction finding system is theoretically possible, but from a practical view point, is very unlikely. At 10 kc/s the wave length is 30,000 meters (18.6 miles) and at 500 kc/s the wave length is 600 meters (0.373 miles). A good directional antenna would have to be several wave lengths in at least one direction. The job of constructing an antenna of these dimensions that could be rotated would be very difficult.

A more practical approach would be to use two or more antennas with fixed locations, and phase and amplitude match their inputs such that the resultant antenna pattern was the equivalent of a sharp beam. This could be done for one frequency without too much difficulty, however, it would be extremely difficult to accomplish this over a wide range of frequencies. The use of a single sharp lobe antenna or antenna system will not be considered further in this report.

2.5 Direction Finding by Phase and/or Amplitude Comparison from Two or More Beamed Antennas.

Figure 2.1 shows two antennas with their beam centers at about 25 degrees apart. A two and one-half degree movement from the axis of one beam causes only a 2.3% change in amplitude. Now consider the case of the two beams acting together. A two and one-half degree movement from the center of the beam pattern gives a 32% change (or difference) in amplitude.

Reference (8) contains a report on the German "Guben" and the "Wullenweber" systems. The "Guben" uses two directional antennas for a sector of approximately 20 degrees. The system essentially matches the



AMPLITUDE MATCHING OF TWO ANTENNA BEAMS

Figure 2.1

phase from the two antennas to obtain a bearing. The advantages of this system are its great sensitivity (improved signal to noise ratio over a single vertical antenna) and its relative freedom from multipath (sky wave) effect. The disadvantages are that it is a sector antenna and it requires a considerable amount of room (especially at the low frequencies of this paper). The "Wellenweber" is a later development of the "Guben" in that an array of antennas are used to obtain 360 degree coverage. The antennas are then sampled in rotation by a rotating coupling unit. The area for such an array would be considerable for the low frequencies.

2.6 Line of Bearings by Null Antenna Systems.

The null antenna or antenna systems are those in most prevalent use today in direction finder systems. In general, these systems use either the loop antenna or the Adcock antenna array. Both of these antennas give the familiar figure of eight pattern in which the amplitude of the signal output is approximately a cosine function.

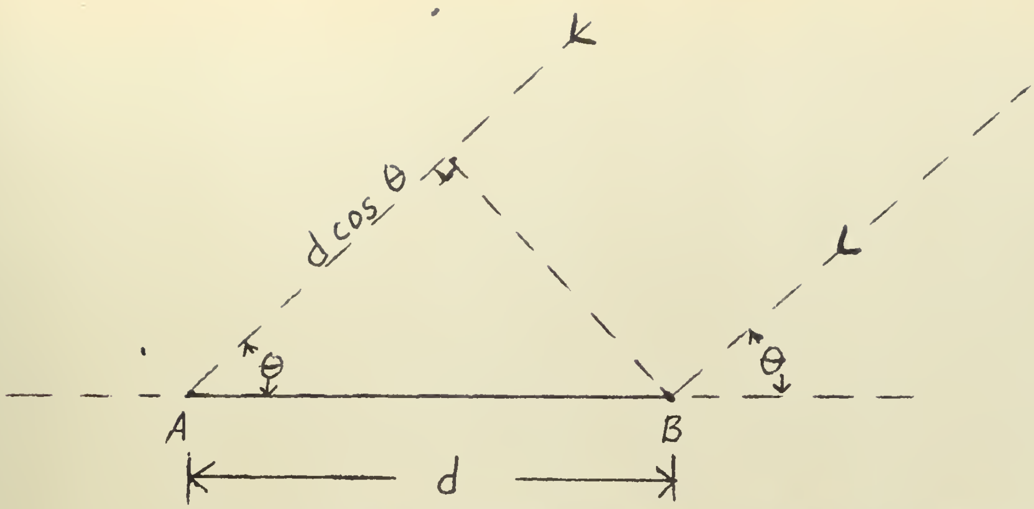
The advantage of the loop is its relatively small size and low output impedance. Its main disadvantage is that it is subject to very large errors from sky wave reception.

The advantage of the Adcock array is that it can be made relatively free of sky wave errors. Its disadvantages are its large size and its high impedance.

Further discussion of these two antennas will be carried out in more detail in Chapter 4 and Chapter 6.

2.7 Line of Bearing by the Time Difference Method.

Figure 2.2 shows the principles of the time difference method. Basically, two non-directional antennas ("A" and "B") are used. The angle of arrival (θ) is obtained by measuring the time difference in the arrival at the two antennas. This angle (θ) is the bearing.



d = distance between the two receiving antennas

θ = azimuth angle of arrival of the signal

c = velocity of propagation = 299692 km/s $\doteq$ 3×10^{8} km/s

t = time

ϕ = phase difference in the signal between points "A" & "B"

$\Delta\theta$ = an incremental change in the angle of arrival

$\Delta\phi$ = an incremental change in the phase angle

Δt = an incremental change in the time difference

λ = is the wave length of the signal

FOR A SHORT BASE SYSTEM

$t = d \cos \theta / c$ in seconds (Equation 10.1)

$\phi = \dfrac{2\pi d \cos \theta}{\lambda}$ in radians (10.2)

$\Delta\phi = \dfrac{2\pi d \sin \theta \; \Delta\theta}{\lambda}$ in radians (10.3)

BASIC TIME DIFFERENCE METHOD

Figure 2.2

A more complete discussion of this system will be found in Chapter 10. The advantages of this system are that it works on a maximum signal, is not theoretically effected by sky wave to any extent, and can be made simple to operate. Its disadvantages are that it requires widely spaced antennas which must be connected to the receiver with cables which have no appreciable pickup. It does have an ambiguity. This ambiguity may be removed by using two sets of antennas placed with their planes perpendicular to each other. This not only removes the ambiguity, but provides a cross check on the bearing.

The system described above may be considered a short base system in which the separation (d) is equal to or less than a wave length. If the separation (d) is many wave lengths then a hyperbolic line of position might be obtained rather than a bearing and there will be numerous ambiguities possible if time difference is measured by phase matching. There are no known short base systems in operational use at the present time. There is a long base system in operation in Germany.

2.8 Doppler Effect.

The doppler direction finder system operates on the effect that as an antenna approaches the source, the apparent frequency of the transmission is increased. Similarly the apparent frequency is decreased if the antenna is moving away from the source.

It is not possible to physically rotate an antenna fast enough in the frequency range under discussion to obtain a useful frequency shift. The antenna may be rotated electrically, however, to obtain this shift. Advantage may be taken in stepping the antenna incrementally to obtain higher order frequency shifts than the theoretical shift.

The advantages to this system are that it can be made relatively free of sky wave error, it can be made uni-directional, and it can be made very sensitive. The disadvantages of this system are that it requires a rather extensive antenna array and fairly complicated equipment. There is a possibility of error from the frequency modulation of the signal at the transmitter. This equipment also requires that the carrier be maintained relatively constant during a period of at least one revolution of the antenna. This essentially limits the use of the system to a certain extent, but this is not as serious as it may seem since the majority of practical systems are limited by this same time consideration.

A more detailed discussion of the doppler direction finder will be found in Chapter 9 and in references (18) and (22).

2.9 Line of Range by the Signal Strength Method.

It would be possible to determine the range to a transmitter by measuring the field strength at the receiver if the transmitter radiated power, attenuation, and complete sky wave information were available. Due to the many factors involved, it is not contemplated that this system will be used except on a comparative basis (the transmitter "seems" close or far depending on the signal strength with respect to some standard).

2.10 Line of Range by the Angle of Arrival of the Sky Wave.

This system holds some practical aspects if the angle of arrival of the sky wave can be very accurately measured in the presence of the ground wave. It would be limited to fairly short ranges (say under 300 miles) on single hop transmissions since at the larger ranges there is very little difference in the angle of arrival for very large increments

in the range. Due to its limitation no great hope can be held for this method as a primary system.

2.11 Line of Range by Measurement of the Time Difference Between the Arrival of the Ground Wave and the Sky Wave or Two or More Sky Waves.

Figure 1.6 gave the time difference in arrival between the ground wave and the first sky wave for several values of effective height. It can be seen that the remarks made in article 2.10 above are also applicable here. In this case, an additional factor would be involved in that a time reference would have to be obtained. This would be fairly difficult even with a signal with a sharp leading edge since the phase shift of the signal is not always predicable during the reflection.

2.12 Line of Range by Around-the-World Time Difference Measurements.

This system is based on the assumption that the difference in length of two paths can be determined by the time difference that it takes for radio waves to traverse these paths. If it is assumed that the paths are great circle routes from the transmitter to the receiver, the distance of the transmitter can be computed unambiguously. One odd thing about this system is that the accuracy of the system is relatively independent of distance. The main problem with this system is that both signals must be received at the same time. Since the signals are not likely to be of the same amplitude an antenna system that is unidirectional is required in order that the signal from each direction can be amplified by its own receiver without interference from the signal coming from the opposite direction. This would involve a very large antenna field for 360 degree coverage. This system is practical at the present time only if the transmitter is very powerful and ionospheric conditions are just right.

2.13 Correlation.

It is fairly obvious that a better bearing can be obtained by observing a signal on a direction finder for 30 seconds than if the signal had only been observed for one second. This is a method of correlation that might be called "time averaging". This method is used extensively in direction finders even though it may be disguised. For instance, a cathode ray tube may have a fairly long persistence which time averages the signal. The operator has a memory by which he mentally time averages a signal. A meter indication or a servomechanism generally have a damping device or integrator which time averages the bearing. Most of these devices can be treated as if they reduced the bandwidth of the system and hence reduced the noise with respect to the signal.

Another method of correlation often used in practice might be called the statistical approach. This is normally used where a large number of bearings or bearings from a number of sources are available. This follows the axiom that if a little bit is good, more should be better.

CHAPTER III

PRACTICAL RADIO DIRECTION FINDERS

3.1 Types of Direction Finders.

Most of the practical direction finder systems will fall into one of two categories, those which accomplish the direction finding before the receiver (such as the simple loop antenna system) or the "Pre-receiver" system, and those which accomplish the direction finding after the receiver (such as the Watson-Watt system) or the "Post-receiver" system. All systems will not fall precisely into either category; some may be a mixture of both. The following is a list of the direction finder systems that will be discussed in the remainder of this paper:

Pre-receiver Systems:

a. Loops

    1. Simple manual loop

    2. Motor driven single loop (continuous rotation)

    3. Servo driven single loop

    4. Parallel loops

    5. Crossed loops with goniometer

b. Adcock

    1. Adcock with goniometer

        a. Manual

        b. Motor driven

        c. Servo driven

c. Single receiver time difference.

Post-receiver Systems:

a. Loop

    1. Watson-Watt

2. Single receiver crossed loops

3. Single loop servo system

b. Adcock

1. Watson-Watt

2. Single receiver

c. Doppler (may also be considered a "Pre-receiver" type)

d. Time difference (two receivers)

3.2 Factors in Selecting a Direction Finder System.

The following factors are some of the points to be considered in selecting a direction finder system for any given job. They are not necessarily in the order of importance.

a. Frequency range to be covered

b. Site requirements

c. Required degree of accuracy

d. Type of signals that may be observed

e. Cost

f. Ease of operation

g. Reliability

h. Ease of maintenance

i. Adaptability to automatic control

j. Ambiguities of the system

k. Types of inherent errors and their magnitudes

l. Sensitivity (ability to operate on weak signals)

CHAPTER IV

ROTATING LOOP SYSTEMS

4.1 Loop Antenna Theory.

It is the purpose of this chapter to discuss first the basic loop antenna and then its application in direction finder equipments. Equations supplied are in almost all cases approximations.

The loop is used in a majority of cases as a sharp null type antenna system. Figure 4.1b shows the familiar figure of eight of the far field loop antenna pattern. It must be emphasized that this pattern is true only if the transmitting source is a long distance from the antenna in relation to the antenna size, the antenna is small in relation to the wave length, and the total length of wire in the antenna is short in regards to one wave length. These assumptions are fairly good ones for the frequency range under discussion (10 kc/s to 550 kc/s) provided that the number of turns in the loop is not too great. It should be noted that the loop antenna need not be circular, but may be of any symmetrical shape. The equations furnished (except for those involving inductance) depend only on the area enclosed by the loop and the number of turns.

The theory of a loop antenna may best be discussed in terms of a square loop (Figure 4.1a). The loop may be discussed in terms of the electric field ($\bar{E}$) or the magnetic field ($\bar{H}$). The $\bar{E}$ and $\bar{H}$ fields are perpendicular to each other and to the direction of propagation ($\bar{P}$) as shown on Figure 4.1c. The polarity of a radio wave is given by the direction of the $\bar{E}$ field. An $\bar{E}$ field that is parallel to a wire will induce a voltage into that wire. It will not induce a voltage in a wire perpendicular to the field. The $\bar{H}$ field on the other hand will induce a voltage in a loop that is proportional to the $\bar{H}$ field that is passing

through the loop. No voltage is induced in the loop unless a component of the $\overline{H}$ field passed through the loop.

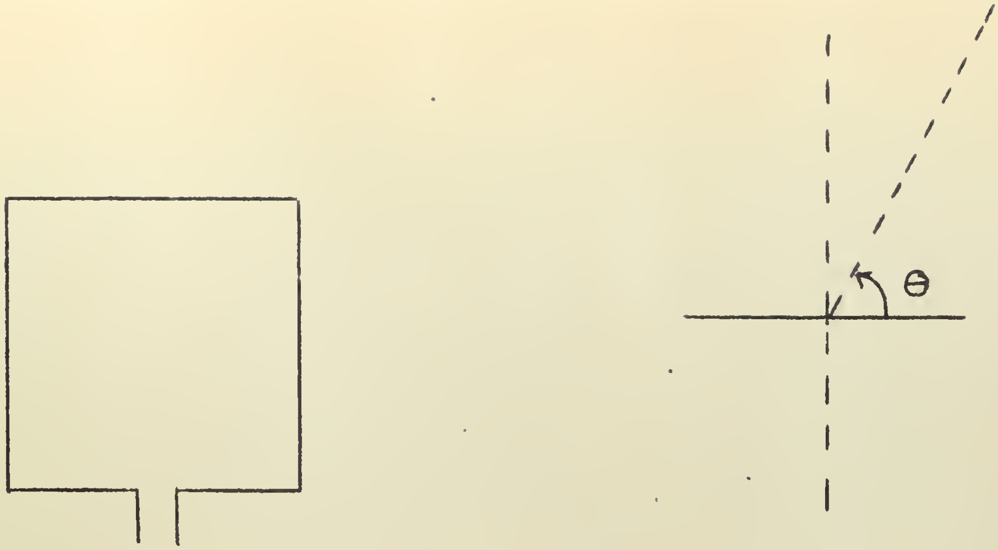
Now to consider the loop antenna of Figure 4.1a, a vertically polarized wave will induce an equal voltage in each vertical arm of the loop ($\overline{E}$ field being considered) and no voltage in the horizontal arms of the loop. The net voltage induced in the loop will depend on the phase of the voltage induced in each arm. It can be seen that the phase difference is zero for a signal arriving at an angle (θ) of 90 degrees and hence there is no output from the loop. The phase difference is maximum for a signal arriving from an angle of zero degrees and hence the loop output is maximum. Equation 4.2 is the induced voltage in the loop antenna and equation 4.3 is the voltage induced in the loop antenna when θ equals zero (maximum voltage induced).

In considering the $\overline{H}$ field and the loop of Figure 4.1a, it can be seen that there is no component of the $\overline{H}$ field passing through the loop when the angle of arrival is 90 degrees and there is maximum $\overline{H}$ field passing through the loop when the angle of arrival equals zero degrees. This gives the same result as when the $\overline{E}$ field was discussed. In future discussions only the $\overline{E}$ or $\overline{H}$ field will be used depending on which one makes for the easier presentation.

The explanation of the action of a loop given above is not entirely satisfactory for a loop located just below the surface of water. In this case, the attenuation of the radio signal by the water plays a big part in the net loop voltage. For further information on underwater loop antennas refer to (15) and (16) in the bibliography.

4.2 Loop Errors.

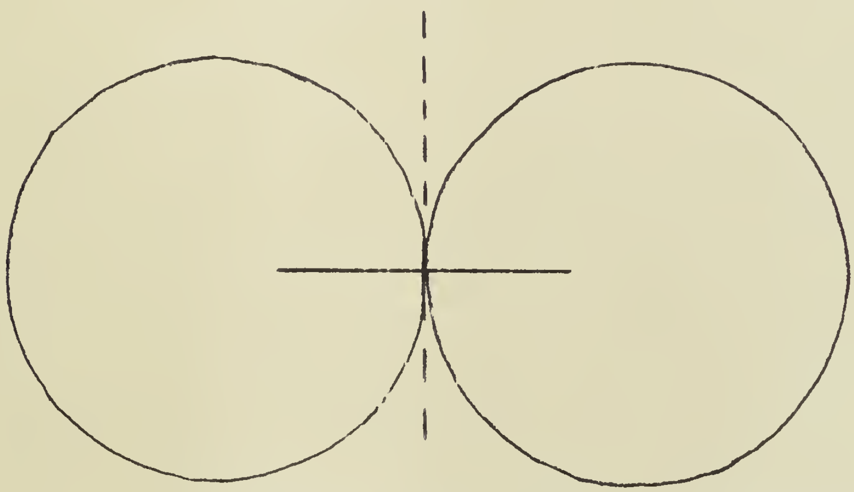
In the case of the simple loop antenna there are two main sources of error. One is due to unbalance in the loop system where the effective



SIDE VIEW TOP VIEW

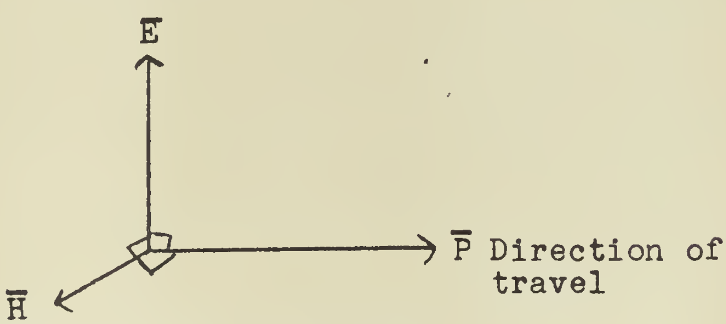
LOOP ANTENNA

Figure 4.1a



FAR FIELD PATTERN OF A LOOP ANTENNA

Figure 4.1b



VERTICALLY POLARIZED WAVE

Figure 4.1c

A LOOP ANTENNA

Figure 4.1

pickup in one side of the loop is not the same as in the other side. This could be caused by unbalanced pickup in the cable connecting the loop to the receiver or pickup in the receiver itself. The result of the unbalance in pickup is apparent since the loop theory depends on exact amplitudes as well as phase match in each loop section for perfect nulls. The magnitude of this problem becomes apparent when one observes that the effective height (he) of a loop antenna (equation 4.4) is very small. As an example the effective height of a loop antenna 50 inches in diameter and with 5 turns is approximately 0.52 inches at 100 kc/s. The results of this unbalance may result in a reduction of the ability to obtain a sharp null or it may actually shift the position of the null.

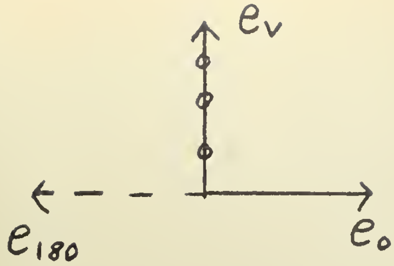
The other major source of error in a single loop antenna system is the polarization error or as it is sometimes known "the night effect". This error is due to the fact that the sky wave arriving at the antenna may contain a component of the $\bar{H}$ field that is in the azimuth direction of propagation. This may be imagined from Figure 4.1c if we consider that the wave is horizontally polarized (change places of $\bar{E}$ and $\bar{H}$ vectors) and $\bar{P}$ is not parallel with the earth but coming down at some angle. It can then be seen that the $\bar{H}$ vector will have a slight forward pitch. It can be seen from this that in order to have polarization error from a single loop that the wave must have some horizontal polarization and must be arriving at an angle to the plane of the antenna. The net effect of this polarization error is to shift the pattern of the antenna. The nulls remain just as sharp as with the ground wave only they are no longer perpendicular to the plane of the antenna. This yields what looks like a true bearing, only the direction is incorrect. Night effect generally makes itself known by the fact that the strength,

polarity, and relative phase of the sky wave varies rather rapidly thus causing the bearing to move rapidly on the presentation.

It would be possible to remove the sky wave error if the antenna were tilted such that its plane were perpendicular to the plane of arrival of the sky wave. This is hardly feasible due to the difficulty in knowing the exact angle of arrival of the sky wave and the fact that this would work only if there were no ground wave or any other sky wave.

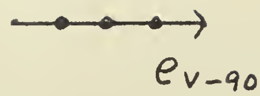
4.3 Sense.

The single, small loop antenna gives two nulls which are 180 degrees apart. In order to remove this ambiguity a "sense" antenna is combined with the loop output to obtain a uni-directional indication. The output from a short vertical antenna has a circular pattern (equal output for all θ's), but is 90 degrees out of phase with the loop antenna output. This short vertical antenna can then serve as a suitable sense antenna if its phase is shifted by 90 degrees. Figure 4.2 shows the principle of the use of a sense antenna. Figure 4.2a shows the relative phase for the three phase vectors representing the outputs of the sense antenna (e_v), the loop antenna when the signal is arriving from 000 degree (e_o), and the loop antenna when the signal is arriving from 180 degrees (e_{180}). Figure 4.2b shows the sense vector shifted by 90 degrees. Figure 4.2c shows the sum of the loop antenna vector for the 180 degree position and the shifted loop vector. It can be seen that the resultant vector is equal to zero. Figure 4.2d shows the sum of the loop vector for 000 degrees and the shifted sense antenna vector. It can be seen that these two vectors are in phase and add. Figure 4.2f shows the far field pattern of the loop antenna alone and the far field pattern of the loop antenna plus the sense antenna shifted in phase by 90 degrees. It can be seen that



RELATIVE VECTORS

Figure 4.2a



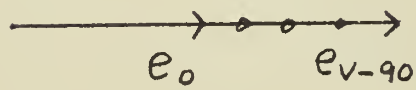
SENSE VECTOR SHIFTED
BY 90 DEGREES

Figure 4.2b

$e_{180} + e_{v-90}$

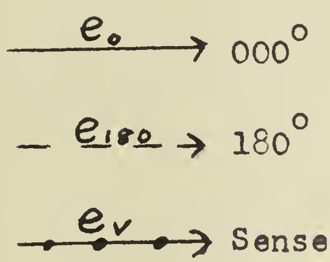
SUM OF LOOP 180 DEGREE
OUTPUT AND SENSE SHIFTED
OUTPUT

Figure 4.2c



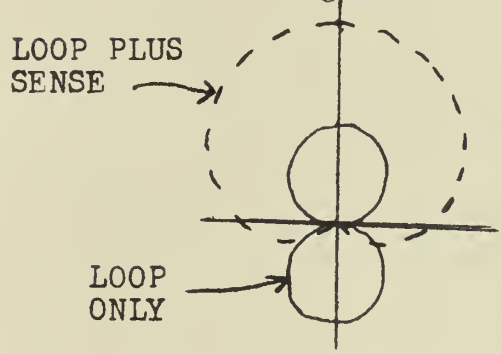
SUM OF LOOP 000 DEGREE
OUTPUT AND SENSE SHIFTED
OUTPUT

Figure 4.2d



VECTOR REPRESENTATION OF
LOOP VOLTAGE OUTPUTS AND
SENSE ANTENNA OUTPUT

Figure 4.2e



OUTPUT PATTERN OF LOOP
ONLY AND LOOP PLUS SENSE
ANTENNA

Figure 4.2f

SENSE

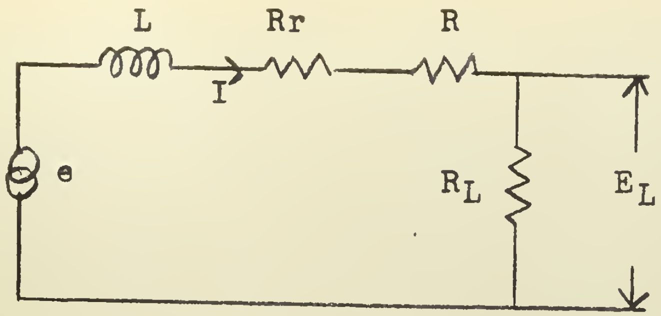
Figure 4.2

the latter gives a far field pattern resembling a cardioid with the single null at an angle of 90 degrees from the loop null. It is possible to use the cardioid null alone for direction finding. This is not generally done, however, due to the fact that precise amplitude and phase from the sense antenna is not always available over a wide range of frequencies to give a perfect cardioid pattern. The general method is to first obtain the bearing with the null of the loop alone, and then determine which of the loop nulls is the correct one by the sense indication.

4.4 Untuned Loop Design Factors.

It might appear from equation 4.2 that any desired voltage output could be obtained from a loop merely by increasing the area of the loop and/or increasing the number of turns in the loop. From a practical viewpoint this is not the case. If we assume that the circuit diagram of Figure 4.3 represents an untuned loop antenna we note that from equation 4.1 that the voltage across the load depends primarily on the radius of the loop. Under normal circumstances Rr and R are much less than R_L, hence $\sum R$ may be considered as approximately R_L. Equation 4.1 indicated that the number of turns is not an appreciable factor, in fact the less the number of turns the better. One thing to note is that although the effective height of the loop increases linearly with frequency (Equation 4.4), the voltage output across the load increases only a small amount with frequency (Equation 4.1). The reason for this is that the inductive reactance of the loop increases with frequency which means that a larger part of the induced voltage from the signal is lost across the loop inductance.

In a practical loop design the size of the loop would be first determined on physical considerations. The number of turns could then be



$e = he\bar{E}$

$I = e/Z = he\bar{E}/\Sigma R + j2\pi fL$

$\Sigma R = Rr + R + R_L$

$E_L = I R_L = he\bar{E} R_L/\Sigma R + j2\pi fL = \dfrac{2\pi^2 N r^2 \bar{E}}{\lambda(\Sigma R + 2\pi fL)}$

$$E_L = \frac{2\pi^2 N r^2 f R_L \bar{E}}{c\left[\Sigma R + j2\pi fN^2 r \mu \left(\ln \frac{8r}{a} - 2\right)\right]} \qquad \text{Equation 4.1}$$

R_L = Load resistance

E_L = Voltage developed across the load resistor

(note: the above equation is an approximation and neglects certain frequency effects)

VOLTAGE OUTPUT OF A LOOP ACROSS A GIVEN LOAD

Figure 4.3

selected which would give the best impedance match to the load. The number of turns could also be selected on the basis of resonating the antenna system at a frequency slightly above the upper frequency than that which is intended for the system.

One important point is that the antenna system should not be self resonant within the band of frequencies over which it is intended to be used.

In regards to noise we shall consider that the receiver noise is equivalent to 0.1 uv at the input terminals of the receiver for a 200 cycle bandwidth. Equation 4.7 can be used to determine the noise developed by the antenna system. In actual design it would be important at this point to compute the signal strength required at the antenna to present a signal level at the receiver which is equal to that of the antenna noise plus the receiver noise (added by the proper method). A comparison of this value of equivalent noise ($\bar{E}eq$) with the noise level expected would indicate whether the atmospheric noise would limit the system or whether the antenna-receiver system would limit it. The desirable case is of course when the atmospheric noise is the limiting factor. In regards to this it can be seen from the previous discussion of ionospheric noise that this is low at the higher frequencies under discussion and increases rapidly as the frequency is decreased. The antenna gain on the other hand does not vary appreciably as the frequency is decreased hence if the system is designed such that ionospheric noise is the limiting factor at the upper end of the band, then atmospheric noise will also be the limiting factor at the lower end of the band. Regardless of which is the limiting factor, however, the signal strength at the antenna must be greater than $\bar{E}eq$ for the direction finder to work properly (true

$$e = \frac{2\pi\ N\ A\ \bar{E}}{\lambda} \cos\theta \quad \sin wt \qquad \text{(Equation 4.2)}$$

$$e_{rms} = \frac{2\pi\ N\ A\ \bar{E}_{rms}}{\lambda} \qquad (4.3)$$

$$he = \frac{2\pi\ N\ A}{\lambda} = \frac{2\pi\ N\ A\ f}{c} \qquad (4.4)$$

$$L = N^2\ r\ \mu\ (\ln \frac{8r}{a} - 2) \text{ henries} \qquad (4.5)$$

$$Rr = 31{,}200\ \left(\frac{N\ A}{\lambda^2}\right)^2 \text{ ohms} \qquad (4.6)$$

$$En = 2\ \sqrt{R\ k\ T \Delta f} \qquad (4.7)$$

$$En = 1.26 \times 10^{-10} \sqrt{R\ \Delta\ f} \quad \text{at approximately 63 degrees F} \qquad (4.8)$$

$$\bar{E}eq = \frac{En}{he} \qquad (4.9)$$

$$Q = \frac{X_L}{R_{series}} = \frac{R_{parallel}}{X_L} \qquad (4.10)$$

$$f = \frac{f_o}{Q} \quad \text{for 3DB down points} \qquad (4.11)$$

$$R_a = \frac{X_L^2}{Rr + R} \quad \text{(see Figure 4.5c)} \qquad (4.12)$$

$$R_{parallel} = \frac{R_a\ R_L}{R_a + R_L} \quad \text{(see Figure 4.5)} \qquad (4.13)$$

$$E_L = e\ Q \quad \text{(see Figure 4.5)} \qquad (4.14)$$

LOOP ANTENNA EQUATIONS

Figure 4.4

for most direction finders where extensive correlation techniques are not used). It is generally assumed that the signal strength should be three or more times $\bar{E}eq$ in order to obtain a usable bearing.

4.5 Tuned Loop Design Factors.

The tuned loop has several advantages over the untuned loop. The tuned loop can reduce the intermodulation components caused by strong signals mixing with the other signals present at the first non-linear device in the circuit (normally the first RF amplifier). The main advantage of the tuned loop is the improvement in signal to noise ratio that is possible.

Figure 4.5a shows the circuit of a tuned loop designed for a low output impedance. Figure 4.5b shows the circuit of a tuned loop designed for a high output impedance. Equation 4.11 gives the bandwidth of a tuned circuit in terms of its Q and the center frequency to which the loop is tuned (Equation 4.10 defines the Q). Figure 4.5c is another way of drawing the circuit of a parallel tuned loop in order to better understand the effect of the load upon the "Q" of the loop.

The circuit of Figure 4.5a permits almost the entire antenna voltage (e) to appear across the load. In addition there is very little noise voltage from the antenna itself.

The circuit of Figure 4.5b permits "Q" times the antenna voltage (e) to appear across the load, but the antenna resistance noise is also much higher than that for the series tuned loop. This circuit works best into a high impedance load whereas the series tuned circuit works best into a low impedance load. In either case the "Q" must be low enough to permit the antenna to have the necessary bandwidth.

The great disadvantage to tuning the loop is that, in any practical system (especially where the loop rotates), it becomes difficult to accomplish. It is used in certain equipments, however. It is seldom used in systems which have more than one loop due to the difficulty of matching the loops in both amplitude and phase.

It is often practical to use a bandpass filter between the loop antenna and the receiver. This gives some of the advantages of the tuned loop in the reduction of cross modulation and some of the advantages of the untuned loop in broad band characteristics and freedom from remote tuning devices.

4.6 Summary of Loop Antenna Information.

a. The effectiveness of the loop is proportional to the area of the loop.

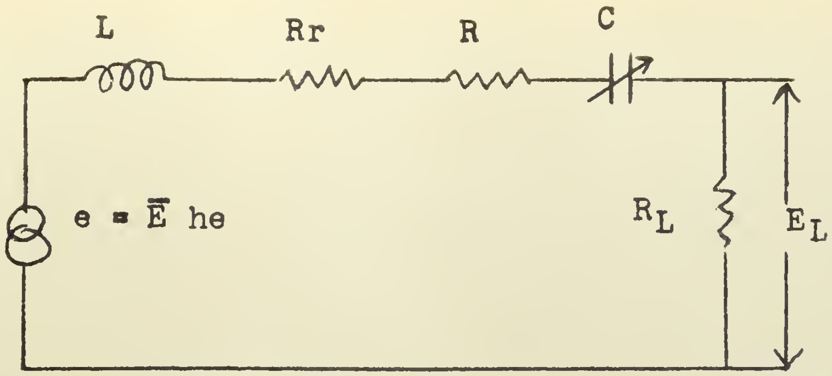
b. The number of turns included in the loop design is normally based on matching problems or the self-resonant frequency of the loop.

c. A loop need not be circular.

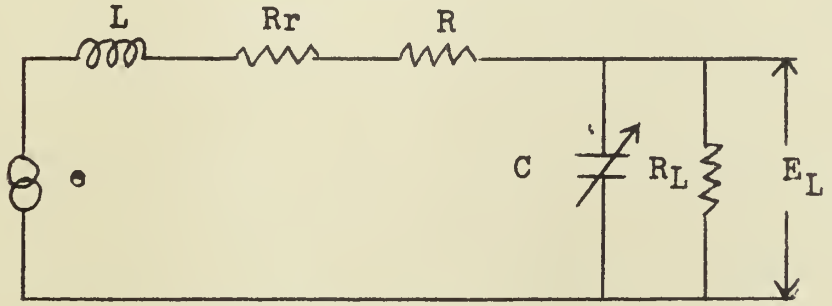
d. The loop may be subject to serious errors due to sky wave transmission.

e. An untuned or bandpass loop circuit is generally employed where a balanced pair of loops are to be used or where it is not practical to tune the loop. A tuned loop may be used to good advantage in increasing the signal to noise ratio in cases where a single loop is used and the tracking of the loop tuning with the receiver tuning is worth the added expense.

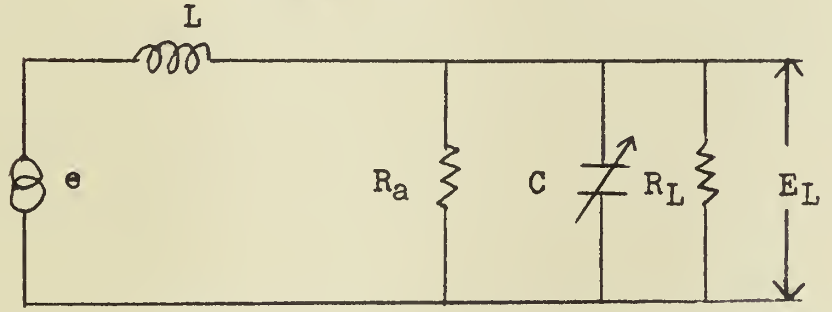
f. It is best to design the loop antenna system for the high end of the band.



SERIES TUNED LOOP
Figure 4.5a



PARALLEL TUNED LOOP
Figure 4.5b



EQUIVALENT PARALLEL TUNED LOOP
Figure 4.5c

TUNED LOOP ANTENNA CIRCUITS
Figure 4.5

4.7 The Single Loop, Manually Operated Direction Finder.

Figure 4.6 is a block diagram for a single loop, manually operated direction finder. The loop may be attached to the receiver and both the loop and the receiver may be rotated or the receiver may remain fixed and only the loop be rotated. In this latter case stops may be placed on the loop rotation in order to prevent twisting the cable or a balanced coaxial transformer may be used to connect the loop and the receiver. This coaxial transformer permits rotation of the antenna without any physical coupling to the receiver.

The receiver may be a standard communications receiver or a special receiver with loop balancing circuits and provisions for mixing the loop antenna and the sense antenna output shifted by 90 degrees. The null and sense indication may be obtained from a signal strength meter (normally part of a good communications receiver) or from the phone output level. Automatic volume control may not be used if the phone output is the method of detecting the null.

The advantages to this system are:

a. It is inexpensive in comparison to other systems

b. It is as accurate as the majority of the loop systems

c. It can be made very sensitive since the bandwidth of the receiver may be very narrow and the loop may be tuned.

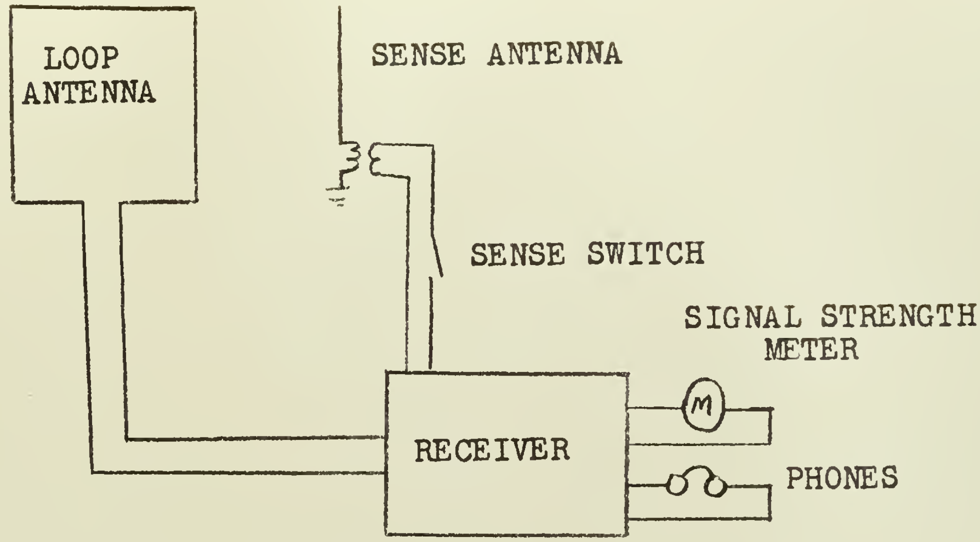
d. It is easy to operate and to maintain

e. An experienced operator may be able to separate several signals that are on the same or near the same frequency

f. The direction finder system does not distort the signal.

The disadvantages of this system are:

a. It is slow in comparison to most of the other systems



A SINGLE LOOP, MANUALLY OPERATED DIRECTION FINDER

Figure 4.6

b. It is not adaptable to automatic operation

c. The system may be saturated by time shared transmitters operating on the same frequency

d. It is bidirectional under normal operating conditions. A simple sense antenna, phase shifting network, and combining network will give the sense as a separate operation.

e. The antenna size is physically limited by the fact that it must be rotated.

4.8 The Single Loop Visual Direction Finder.

The single loop visual direction finder is an advanced modification of the single loop manual direction finder. The visual direction finder permits the loop to rotate continuously and the bearing is indicated on the face of a cathode ray tube. Figure 4.7 is the block diagram of one type of visual direction finder.

The success of this system depends on the rotating magnetic deflection coil of the cathode ray tube maintaining synchronism with the rotation of the loop such that a current through the magnetic coil will deflect the electron beam towards the outer periphery of the cathode ray tube in a direction that corresponds to the null of the loop. An important factor in obtaining a sharp bearing is the fact that the normal field pattern of the loop is reversed on the cathode ray tube. Figure 4.7b shows that the no signal position of the scope pattern is at the outer periphery of the scope (null position) whereas the strong signal condition has the electron beam at the center of the scope. This gives the sharp bearing pattern of Figure 4.7c. The sense pattern is shown in Figure 4.7d. This pattern resembles a reversed cardioid (seldom an exact one) which gives an uni-directional null position at right angles

to the bearing pattern. The correct bearing is determined by the location of the sense null or maximum with respect to the two bearings obtained in Figure 4.7c. In most practical direction finders the sense pattern of Figure 4.7d is rotated by 90 degrees in order that the maximum will be in the direction of the true bearing (some systems use the maximum in the opposite direction of the true bearing).

The antenna drive motor need not be coupled mechanically to the cathode ray tube deflection yoke, but may be coupled electrically through a servomechanism or a synchro system.

Another variation of this system uses a four deflection plate (electrostatic deflection) type cathode ray tube. The circular sweep is obtained by furnishing the same signal to both sets of plates, but with 90 degrees phase difference. A good example of this system is the AN/SRD-7 direction finder.

The advantages of the single loop visual direction finder system are:

a. It provides a bearing on a relatively short signal (actual time depends on rotation rate of antenna)

b. It can be made very sensitive

c. It is easy to operate and to maintain

d. The system will work on time shared transmitters on the same frequency provided that the period that each transmitter is on is at least equivalent to several rotations of the antenna

e. Provides some correlation in time due to the persistance of the cathode ray tube.

The disadvantages of this system are:

a. The signal is distorted by the direction finder process

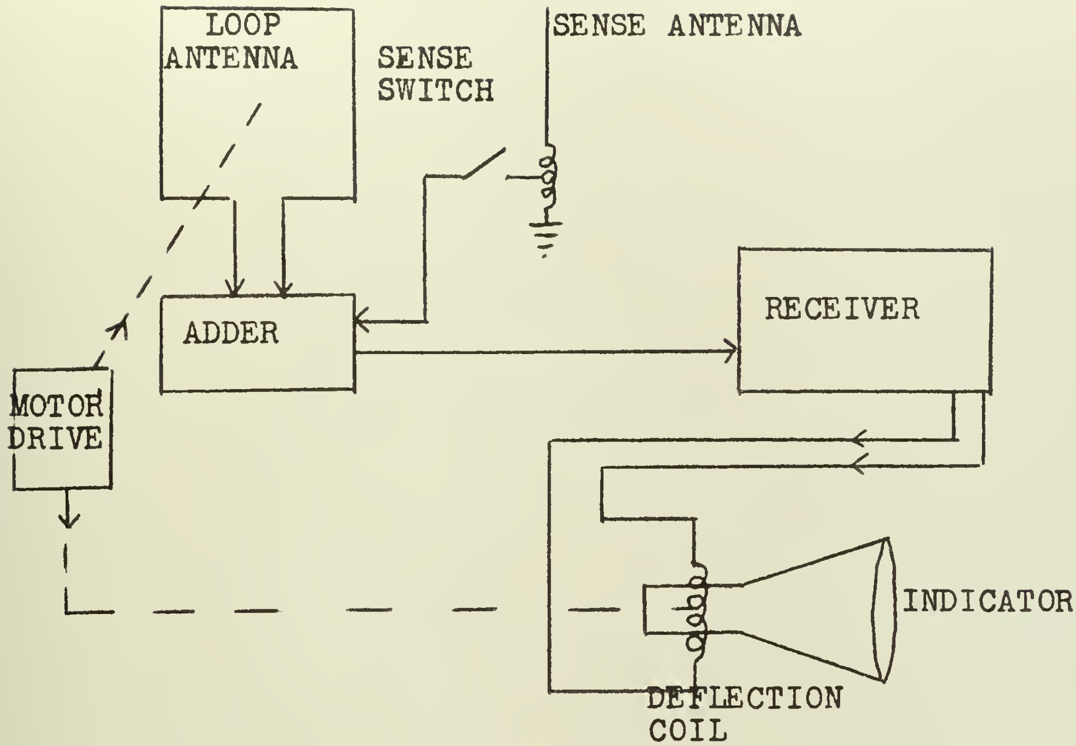
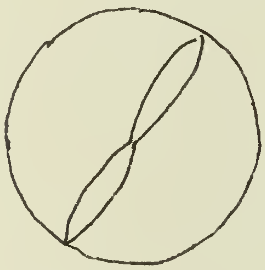


Figure 4.7a

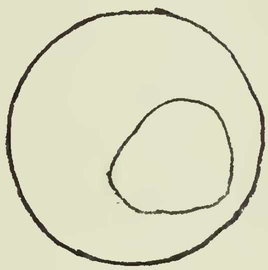
NO SIGNAL

Figure 4.7b



SIGNAL

Figure 4.7c



SENSE

Figure 4.7d

SINGLE LOOP VISUAL DIRECTION FINDER

Figure 4.7

b. Two signals which are on or near the same frequency at the same time may completely destroy the bearing information.

c. The bearing is bidirectional (the sense position is separate from the "bearing" position).

d. The antenna size is limited by the physical fact that it must be rotated at fairly high speeds.

e. An appreciable modulation component in the signal (either amplitude modulation or due to pulse repetition rate) that is near the frequency of rotation of the antenna will provide distorted bearing patterns.

f. The antenna may not be coupled to the receiver via a mechanical coupling.

4.9 The Single Loop Automatic Direction Finder.

The single loop automatic direction finder was introduced primarily for aircraft use. The direction finder automatically aligns the single loop antenna onto the transmitter bearing and indicates this bearing where the operator (or pilot) may observe it. All that is required from the operator is to tune in the signal. The bearing that is obtained is uni-directional.

This paper will consider two basic methods for this type direction finder. The first method (Figure 4.8) uses a two phase motor and aligns the antenna null onto the transmitter. The second methods uses amplitude matching of two beams as shown in Figure 2.1. The block diagram of this system is shown in Figure 4.9.

In reference to the first method (Figure 4.8), the antenna drive motor is a two phase motor. This motor will revolve in one direction if the power amplifier furnishes a voltage 90 degrees ahead of the reference

voltage and will revolve in the opposite direction if the voltage is 90 degrees behind the reference voltage. In order to discuss this system the frequencies and their phases are given below for each of the lettered points on the block diagram of Figure 4.8. No amplitude is given and only the important frequencies are considered. There are other frequencies present at different points, but they are filtered out or neglected in this circuit. The column headed by a (1) will be for a signal arriving from the right hand side of the loop and the signal arriving from the left hand side of the loop will be under colume (2).

	(1)	(2)
A	$\cos w_1 t$	$\cos (w_1 + \pi)t$
B	$\cos w_2 t$	$\cos w_2 t$
C	$\cos(w_1 + w_2)t + \cos(w_1 - w_2)t$	$\cos(w_1+w_2+\pi)+ \cos(w_1-w_2+\pi)t$
D	$\cos w_1 t$	$\cos w_1 t$
E	$"D"_1 + "C"$	$"D"_2 + "C"$
F	$\cos w_2 t$	$\cos(w_2 + \pi)t$
G	$\cos(w_2 + \frac{\pi}{2})t$	$\cos(w_2 + \frac{\pi}{2})t$

w_1 = the signal frequency

w_2 = the reference voltage frequency

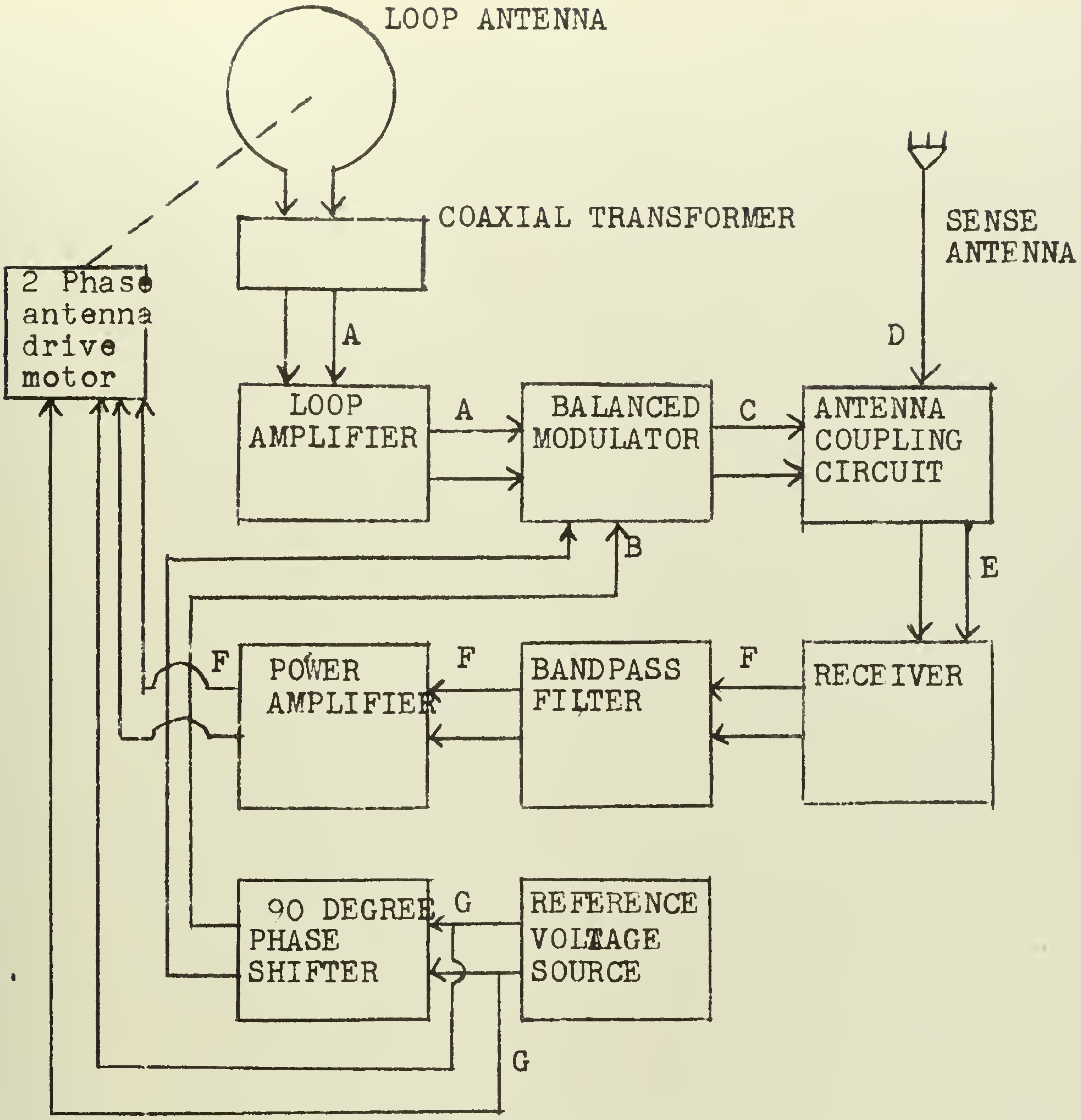
The first point of importance on the block diagram is the "Balanced Modulator". This unit takes the two signals ("A" and "B") and mixes them such that their sum and difference frequencies less the original frequencies appear at the output ("C"). This gives the same type of signal as an amplitude-modulated, suppressed carrier signal. The sense antenna signal is shifted by 90 degrees in order that it be in phase with the original carrier ("A_1") or 180 degrees out of phase ("A_2") and then it is mixed with "C" to obtain a double side band amplitude modulated signal with carrier "E". This signal is sent to the receiver where it is

amplified and detected. The amplitude envelope (modulation) "F" goes from the receiver to the bandpass filter which filters out the "w_2" from the rest of the signal. This signal "F" is then sent to the power amplifier and then on to the motor.

At first thought it might appear that the motor would always be turning in one direction or the other. Such is not the case. The amplitude of the voltage output from the power amplifier is directly dependent on the amplitude of the signal voltage at point "A". This is due to the fact that the amplitude of the output voltages from the balanced modulator depends on the amplitude of both of its input voltages. If either voltage goes to zero, the output "C" goes to zero. It can then be seen as the antenna is rotated into the null, the power amplifier furnishes less and less power to the motor until the time when the signal arrives at the antenna from the null bearing, then there is no power "F" supplied to the motor. Power from the voltage reference source "G" is always furnished to the motor at a constant level.

A variation of this system uses another balanced modulator with voltages "G" and "F" as the input. The output in this case is a Direct Current whose amplitude depends on the amplitude of the signal at "A" and whose sign depends on the direction of arrival. This DC voltage can then drive a DC motor in the proper direction for a null. In either case, the bearing is uni-directional since there is little likelihood of the antenna being on the reverse signal and staying there.

The second method for an automatic direction finder is shown in Figure 4.9. In this case a single loop antenna and a vertical sense antenna are used. The polarity output of the loop is shifted 180 degrees at a rate set by the multivibrator control (what is shown is the sense



AN AUTOMATIC LOOP DIRECTION FINDER (1)
Figure 4.8

antenna being shifted, the effect is the same as though the loop phase were shifted). The loop antenna output and the sense antenna output are then combined and sent to the receiver. It should be noted that one combination of the loop and the sense antenna give a cardioid type pattern with the null to the left. The other combination gives a cardioid type pattern with the null to the right. The "on" bearing condition in this set is when the output of the two cardioid patterns are equal. In this case the receiver will receive a signal without any modulation due to the switching between the two conditions. Should the antenna be "off" bearing then an amplitude modulation is superimposed on the signal which after demodulation by the receiver goes to the control amplifier. The control amplifier amplifies this signal and compares it in phase with the multivibrator control to determine in which direction the antenna must go to approach the correct null. It then sends a DC current to the antenna drive motor which rotates the antenna to the null position.

The advantages of the Automatic Direction Finder Systems are:

a. Can be made fully automatic in tracking

b. Provides some correlation in time hence it may be able to track a signal that would be too weak for some of the other equipments.

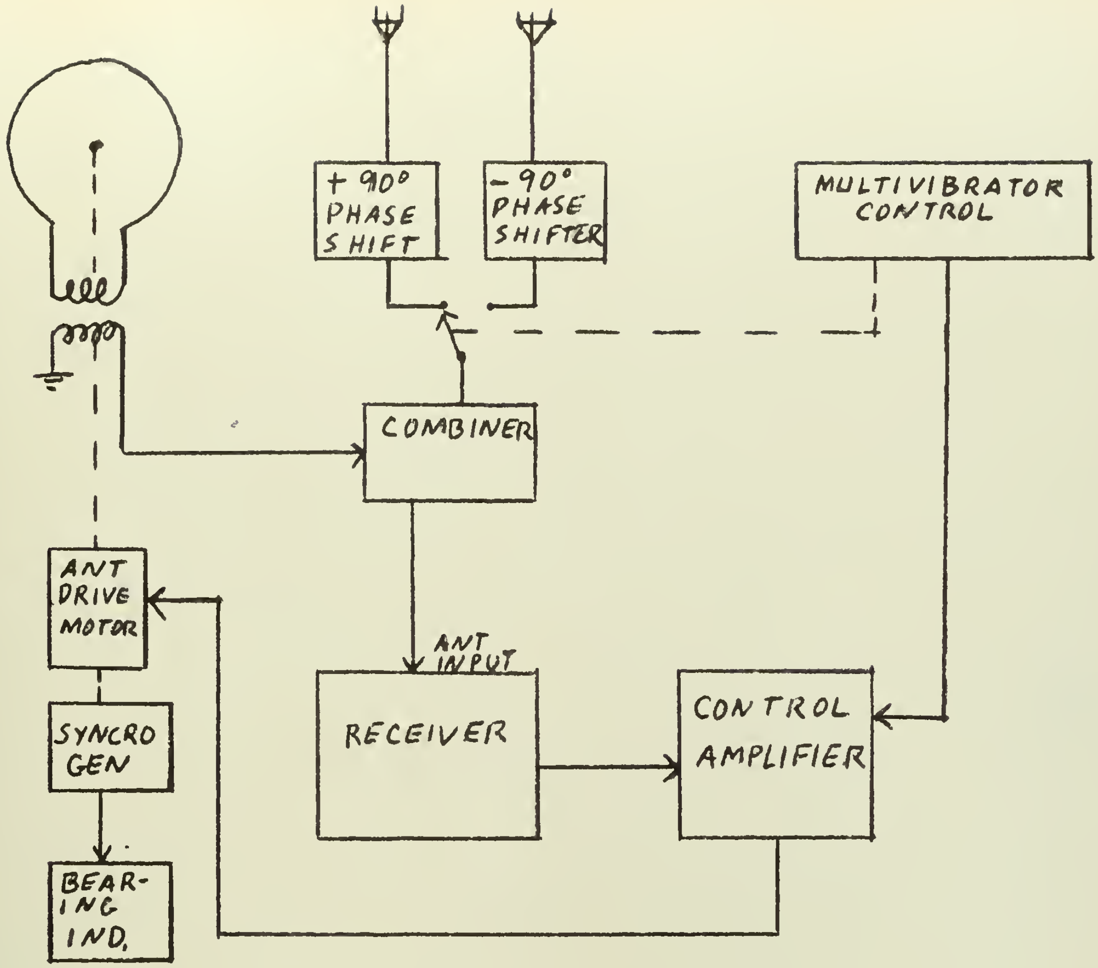
c. It is as accurate as the majority of loop direction finder systems

d. It is fairly easy to maintain and very easy to operate

e. The first type of direction finder does not appreciably distort the signal. The second type does amplitude modulate the signal while it is off bearing.

Disadvantages of the Automatic Direction Finder Systems are:

a. It is slow in comparison to most of the other systems



AN AUTOMATIC LOOP DIRECTION FINDER (2)

Figure 4.9

b. The system may be disabled by transmitters which time share a given frequency (some help here may be obtained if the output voltage is metered. This would provide some indication of bearing of the different signals provided that each was not on too short a time).

c. The system is not very effective against very short pulse type signals

d. The system could be disabled if the signal being DF'ed contained a strong amplitude modulation component equal to the reference frequency or switching frequency

e. The antenna size is limited by physical considerations involved in rotating it by a servo system.

4.10 The Parallel Loop Direction Finder.

The parallel loop direction finder (also known as the "spaced loop direction finder") was one of the early attempts to avoid polarization or night error. Figure 4.10 shows the method of connecting two parallel loops spaced a distance "d" apart such as to give one output which may be treated similiarly to a single loop output in some respects. The polarization error in each loop is equal, but the connections cause the two errors to be opposite in phase and hence balance each other out. Equation 4.15 gives the output of the array in terms of the angle of arrival (θ). It can be seen that this is a four lobed pattern with four nulls. The greatest price paid in this arrangement is the very low sensitivity. The separation "d" would have to be almost 1000 meters (0.6 miles) at a frequency of 100 kc/s in order that the parallel loop would have the same effective height as one of its loops used alone.

The spaced loop, due to its size and the fact that it is not a simple cosine function array, will almost always be constructed as a manual direction finder. It may be used to advantage on the higher frequencies, but it is unlikely that it will be used on the lower frequencies due to the very large spacing that would be required and the fact that the antenna array must be rotated about a center midway between the two antennas.

The parallel loop is subject to errors caused by an unbalance in the two loops or distorted field patterns.

Advantages of the parallel loop:

a. Not susceptible to polarization error

b. Its signal level output does not decrease appreciably for high angles of arrival as does the Adcock antenna.

c. It is very accurate when sufficient signal strength is available

d. Is easy to maintain and fairly simple to operate

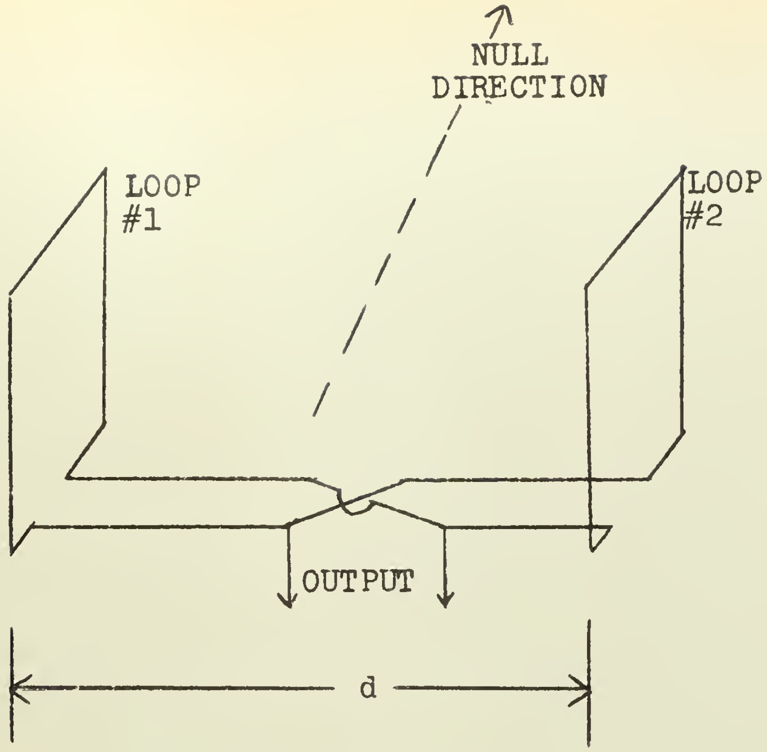
e. An experienced operator may be able to separate several different stations on or near the same frequency.

Disadvantages of this system:

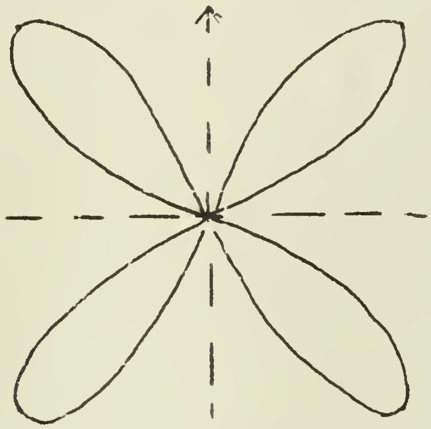
a. Very low sensitivity at the lower frequencies

b. Extremely slow operation

c. The antenna size and spacing is physically limited by the fact that the antenna array must rotate about a point midway between the two antennas.



PARALLEL LOOP ANTENNA



PARALLEL LOOP ANTENNA PATTERN

$$e = he \frac{\pi d}{\lambda} \bar{E} \sin 2\theta \qquad \text{Equation 4.15}$$

$$he = \frac{2\pi NA}{\lambda} \qquad \text{Equation 4.4}$$

THE PARALLEL LOOP ANTENNA

Figure 4.10

CHAPTER V

FIXED LOOP DIRECTION FINDER SYSTEM

5.1 Direction Finding Systems Using Fixed Loops.

The previous chapter dealt with loops which were physically rotated to accomplish the direction finder function. The first major improvement over the rotating loop was to construct two loops at right angles to each other and to rotate these loops electrically. There are two basic systems to accomplish this task. The earliest system known as the "Bellini-Tosi" system makes use of a radio goniometer ahead of the receiver whereas a later system known as the "Watson-Watt" system makes use of a cathode ray tube (or two amplitude recorders) following the receivers. The "Bellini-Tosi" system will be discussed first and "Watson-Watt" system will be discussed under the "Post-receiver" systems in a later chapter.

5.2 The Radio Goniometer.

One method of obtaining the electrical effect of rotating an antenna without physically rotating the antenna system is by the use of a radio goniometer. In order to be successful the goniometer-antenna combination must produce the same effect as if the loop itself were being rotated. The goniometer is a cosine device hence it will work with antenna systems which have a cosine pattern such as the loop antenna and the Adcock antenna system. The goniometer is constructed very similar to an electric motor. Figure 5.1 is two representations of the radio goniometer. The goniometer is so constructed that the mutual inducance between each effective pair of primary coils (Figure 5.1b) and the rotating coil is proportional to the cosine of the angle that the axis of the rotating coil makes with the axis of the primary coils (L1 and L2).

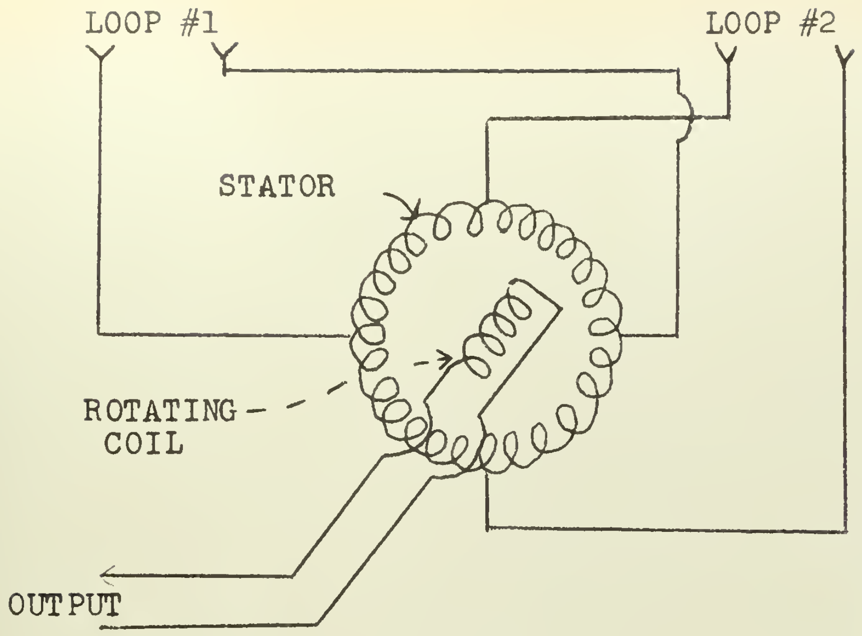


Figure 5.1a

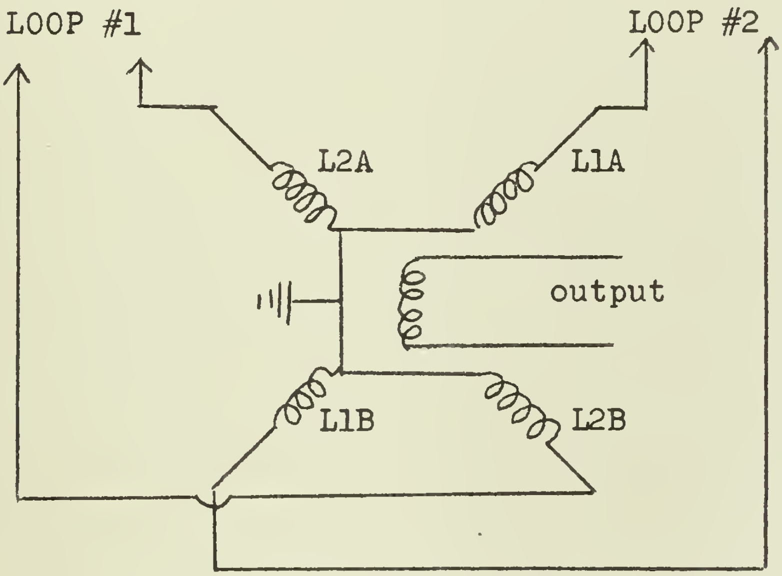


Figure 5.1b

A RADIO GONIOMETER

Figure 5.1

The radio goniometer may also be used as a source of two voltages to provide a circular sweep on an oscilloscope.

5.3 Crossed Loop Antenna Systems.

Article 5.2 showed that a pair of crossed loop antennas coupled into a properly designed goniometer could be used to give approximately the same input to a receiver as a single loop that was physically rotated. The advantage to this system is that the crossed loops may be made considerably larger than the single loop (at frequencies where the size of the loop does not become appreciable in respect to the wave length) since the crossed loops are permanently fixed in space. The extra gain available via this method is not entirely realized due to the losses in the goniometer and associated circuitry. It is also not practical to tune crossed loops such that they are a high Q circuit. The reason for this is that the gain of each loop must be nearly identical to the other loop for accurate bearings. As an example, if one loop had a gain that was 3DB different (0.707 of the voltage) from the other loop then a possible error of approximately ten degrees would be observed. The amount of error due to this source depends on the angle of arrival of the wave front with respect to the fixed loops. The error is maximum when the angle of arrival is at a 45 degree angle to each of the loops and is zero when the angle of arrival is perpendicular to one of the loops.

Polarization error affects the crossed loops in the same manner that it affects the single loop. Another error that is possible in the crossed loops that is not encountered in the single rotatable loop is the error caused by the two loops not being exactly at 90 degrees electrically to

each other and to the ground plane. The radio goniometer is also a possible source of error since it is subject to the same errors due to unbalance as are the loops.

The crossed loop-goniometer system could be used as a manual direction finder in which case the operator would merely rotate the rotor of the goniometer to obtain the bearing, or the combination may be used as an automatic direction finder with the servo system controlling the position of the rotor of the goniometer. The former system is used in a few cases in which large antennas are desired and ease of operation is required. The author knows of no case in which the latter system is used. The reason that the above two systems are not used to any extent with the crossed loops (other than as a manual back-up to the visual system) is that the crossed loop-goniometer system lends itself ideally to the visual direction finder system. Article 4.8 explained the principles of the visual direction finder. The major modification of the single loop system to convert to a crossed loop system would be that the input to the receiver would come from the rotor of the goniometer instead of the single loop and the mechanical coupling to the single loop would be transfered to a mechanical coupling to the rotor of the goniometer.

Advantages of the crossed loop-goniometer system:

a. Larger loops may be used than is practical for a rotating loop system.

b. The effective antenna rotation speed can be made very high.

c. The maintenance is generally less than that required for a high speed rotating loop system.

d. The advantages of the simple loop system may be easily built into the visual direction finder system as an auxiliary feature.

Disadvantages of this system are:

a. There are more sources of error in this system than for the single rotating loop antenna

b. A high speed rotation of the goniometer will effectively modulate the signal with the rotation frequency

c. Signals on or near the same frequency can destroy the bearing accuracy of the visual system

d. Obtaining a bearing on a short pulse signal may be very difficult (note: this type of direction finder is sometimes referred to as an instantaneous direction finder which it definitely is not, as an appreciable signal period is required to obtain an accurate bearing with this system)

e. It is a bidirectional system with an auxiliary sense system required for sense determination (relatively easy to engineer into the system)

f. An appreciable modulation of the carrier at a frequency near that of the goniometer rotational speed may distort the bearing pattern on the scope.

CHAPTER VI

ADCOCK DIRECTION FINDER SYSTEMS

6.1 The Adcock Antenna.

The Adcock antenna system was introduced to reduce the sky wave error which is found in most loop antenna systems. Figure 6.1 shows several methods of connecting vertical antennas to form an Adcock antenna. Essentially the Adcock antenna may be thought of as a loop antenna with the top section missing. This then theoretically permits only the vertical component of the $\bar{E}$ field to induce voltages into the antenna system. Figure 6.2 shows that if the two vertical antennas are connected such that the voltages induced in each antenna subtract then the output voltage of the Adcock is essentially the same as for a loop antenna of the same area and it obeys the cosine law of the loop to the extent that equation 6.1 equals equation 6.2. This is approximately true over the frequency ranges under consideration and for practical sizes of Adcock arrays. The error that is developed due to the difference in the two equations is known as the "Octantal" error and is negligible if "d" is less than one-tenth of a wave length. A spacing of one-fifth of a wave length gives approximately a one degree "octantal" error.

6.2 Sensitivity of the Adcock Antenna.

It was pointed out in the preceeding article that the Adcock antenna is essentially the same as a one turn, non-tuned loop antenna. Since the Adcock is limited to effectively one turn, the area of the Adcock is made as large as possible to increase its effective height within the limitations of the octantal error explained above. This makes the Adcock antenna too large to be physically rotated for the frequencies under consideration hence the Adcock system is almost always used in the manner

of the crossed loop antenna system. Figure 6.3 shows a vertical antenna and an equivalent circuit. Due to the higher impedance of the vertical antenna than that of the loop, the losses in matching the vertical antenna to the receiver are generally greater than those of the loop antenna. Another feature that reduces the effectiveness of the Adcock antenna is that the effective area of the antenna falls off as $\cos^2 \alpha$ as shown by equations 6.4 and 6.5 of Figure 6.2. Thus as the angle of arrival increases the output of the antenna falls off very rapidly. Fortunately in the frequency range of interest we are not apt to find the angle of arrival being very large when outside the ground wave transmission path. It is generally recommended that a minimum spacing of one-fifteenth of a wave length be used to maintain adequate sensitivity over a three to one bandwidth.

6.3 Adcock Antenna Errors.

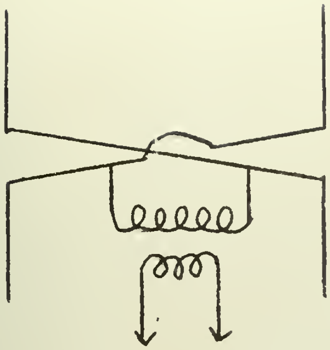
Articles 6.1 and 6.2 treated the Adcock antenna as though it had no polarization error. This would be true only if there were no component of horizontal pickup in the antenna system. Figure 6.1 shows some of the methods of connecting the two vertical antennas to form an Adcock antenna. In order to compare the polarization effect on different types of direction finder systems the "Standard Wave" error is often used as a reference. The "Standard Wave" error is defined as the polarization error due to a sky wave arriving at an angle of 45 degrees to the earth's surface and with a plane polarization of 45 degrees. Barfield in the Institute of Electrical Engineers Journal of April 1935 gave the following values of "Standard Wave" error for the antennas shown on Figure 6.1:

Figure	Standard Wave Error
6.1a	2 degrees
6.1b	6 degrees
6.1c	12 degrees
6.1d	6 degrees
6.1e	1 degree
6.1f	less than one degree

The "Standard Wave" error of the loop antenna in comparison is given as 35 degrees. These values are probably on the optimistic side for practical low frequency Adcock systems.

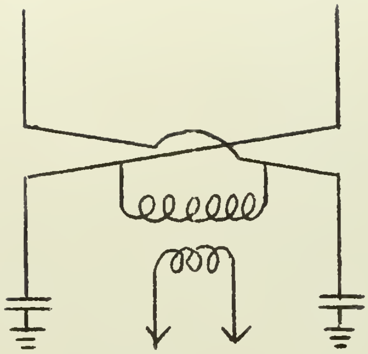
Octantal or spacing error was treated in article 6.1. It might be noted also that any deviation in the goniometer away from the cosine law operation would also introduce an octantal error. It has been shown (20) that this octantal error may be reduced by using more than four vertical antennas (comparable to the crossed loop antenna system) in an Adcock antenna system. It has also been shown (20) that the maximum practical number of vertical antennas in an Adcock system are eight. Any increase beyond this number does not provide a worthwhile increase in accuracy. These systems require a special radio goniometer.

Quadrature error encountered in a four pole (excluding the sense antenna which is normally mounted in the middle of the Adcock antennas) Adcock system is normally due to either an unbalance in the two Adcock antennas or is due to reradiation from some near-by conductor. The high impedance Adcock antennas are very subject to unbalance due to changing ground conditions.



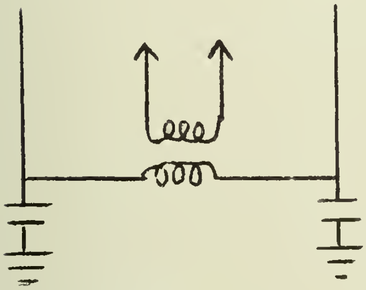
SIMPLE "H" ADCOCK
(Remote from earth)

Figure 6.1a



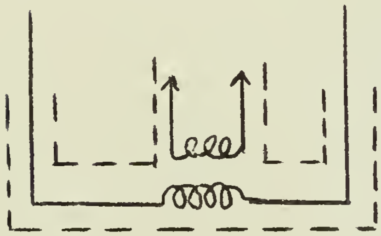
BALANCE ADCOCK
(Close to earth)

Figure 6.1b



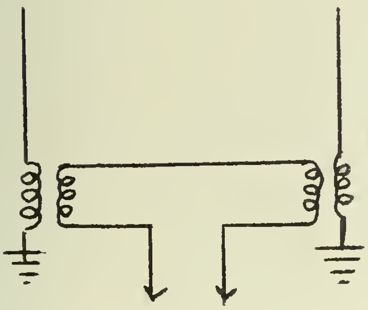
"U" ADOCK
(Near earth)

Figure 6.1c



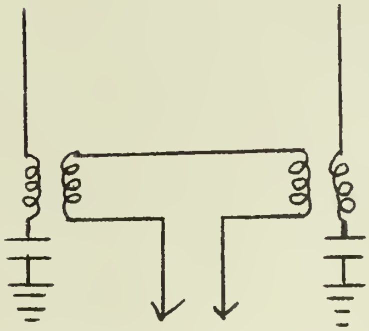
SHIELDED "U" ADCOCK
(Close to earth)

Figure 6.1d



COUPLED "U" ADCOCK
(Close to earth)

Figure 6.1e

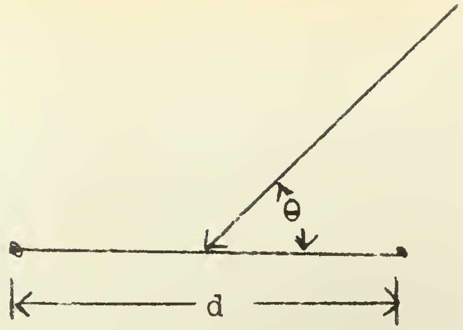


BALANCED COUPLED "U" ADCOCK
(Close to earth)

Figure 6.1f

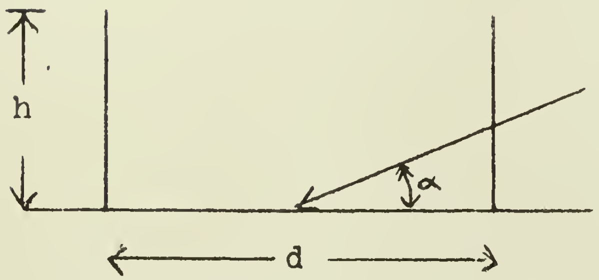
ADCOCK ANTENNAS

Figure 6.1



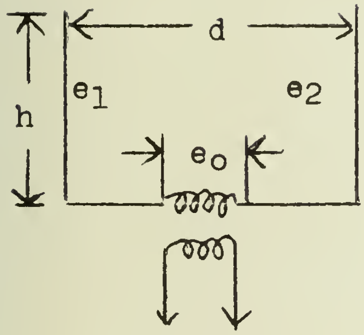
PLAN VIEW OF AN ADCOCK ANTENNA

Figure 6.2a



SIDE VIEW OF AN ADCOCK ANTENNA

Figure 6.2b



A "U" ADCOCK ANTENNA

Figure 6.2c

$$e_o = e_1 - e_2$$

$$e_o = 2\, e_1 \sin \frac{\pi d \cos \theta}{\lambda} \quad \text{(Eq 6.1)}$$

$$e_o \approx 2\, e_1 \frac{\pi d \cos \theta}{\lambda} \quad \text{(Eq 6.2)}$$

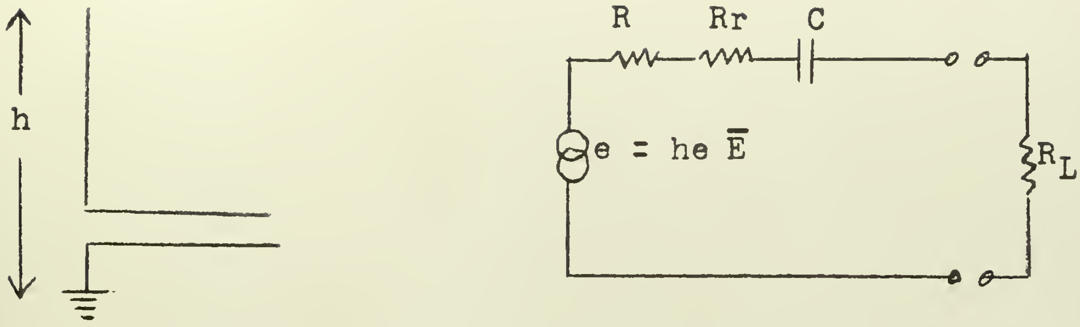
$$he = \frac{2 \pi h\, d}{\lambda} \cos \theta \quad \text{(Eq 6.3)}$$

$$h' = h \cos \alpha \quad \text{(Eq 6.4)}$$

$$d' = d \cos \alpha \quad \text{(Eq 6.5)}$$

ADCOCK ANTENNA EQUATIONS

Figure 6.2



A VERTICAL ANTENNA AND A SIMPLIFIED EQUIVALENT CIRCUIT

$$he = \frac{\lambda \sin^2 \left(\frac{\pi h}{\lambda}\right)}{\pi \sin \frac{2\pi h}{\lambda}}$$ (for $h \leq /4$) (Eq 6.6)

$$he \approx \frac{h}{2}$$ (for frequencies and practical antenna heights of this paper) (Eq 6.7)

$Rr + R \approx 1$ ohm

$C \approx 200$ uufd

for a 72 foot tower with a good ground plane

A VERTICAL ANTENNA

Figure 6.3

6.4 Adcock Direction Finder Systems.

There is little need of illustrating all of the systems using the Adcock antenna since the Adcock antenna gives essentially the same far field pattern as does the loop antenna. Any of the systems shown for the crossed loop antennas is adaptable to the Adcock antenna merely by substituting the Adcock antenna for the loop antenna and rematching the impedances.

The advantage of using the Adcock antenna system in place of the crossed loop antenna system is that the Adcock antenna system can be made relatively free from polarization errors.

The disadvantages of an Adcock antenna system compared to a loop antenna system are:

a. The Adcock antenna system requires more space than does the corresponding loop.

b. It is generally more difficult to balance an Adcock system than a loop system.

c. The Adcock system is more sensititive to ground conditions than is the loop.

d. It is not practical to operate the Adcock antenna as a single rotating element at these frequencies hence a goniometer or a variation of the Watson-Watt system must be used.

CHAPTER VII

POST-RECEIVER DIRECTION FINDER SYSTEMS USING MULTIPLE RECEIVERS AND CROSSED LOOPS OR ADCOCK ANTENNAS.

The post-receiver direction finder systems are characterized by the fact that the signal is supplied to the receiver directly from the antenna with the techniques for obtaining the directional information applied to the signal after it leaves the receiver. The most important of these systems is known as the "Watson-Watt" system. At the present time this system is one of the few (and the most practical) that can give a truely instantaneous bearing on a single short pulse. Figure 7.1a is a block diagram of one possible Watson-Watt direction finder. The system shown is a three receiver, uni-directional system. The system may be simplified to a two receiver system as shown in Figure 7.2 in which case bi-directional bearings are obtained.

The antennas in this system have the same advantages and disadvantages as for any other crossed loop or Adcock system. In reference to Figure 7.1, the two receivers which amplify the loop antenna signals must be both amplitude and phase balanced. The amplitude match of the system (includes antennas, receiver, and cathode ray oscilloscope) is the most important factor. As an example a ten percent difference in overall gain between channels #1 and #2 may produce three degrees of error in bearing. A 50% difference in gain could produce an 18 degree error in bearing. The phase shift difference on the other hand is mostly an inconvenience for values up to, say, 20 degrees difference since this merely makes the pattern on the scope tend toward a circle rather than a straight line. There is no appreciable bearing error due to this phase shift difference. The sense channel need not be amplitude balanced to the other channels

and need be phase balanced only to about 20 degrees (this is arbitrary) in order that it might provide a clear indicating of the correct quadrant (note: there is a 90 degree phase shift in the sense system to permit the sense and the other two signals to be in the proper phase relationship as has been explained previously in chapter 4). The output of the sense receiver should be clipped to provide essentially a square wave pattern for the sharpest sense indication on the scope.

A two receiver Watson-Watt system is shown in Figure 7.2. The receivers in a Watson-Watt system may be either of the tuned radio frequency type or of the superhetrodyne type. In this case a double conversion superhetrodyne is used. The essential item in this type of receiver is that the conversion oscillators must be common to all receivers. Each receiver channel must be completely isolated from the other channel or else cross talk will destroy the accuracy of the system. The "Signal Source" shown in the block diagram is used to align both channels as to gain and phase. In this case the "Signal Source" derives its frequency from the first converting oscillator of the receivers and a crystal oscillator. The amplitude of the "Signal Source" must nearly match that of the input signal hence the amplitude of the "Signal Source" is controlled by the gain setting of receiver #1 which presumably has been set to match the input signal from the loop antenna. Receiver #2 is matched in phase and gain to receiver #1 by the "Amplitude and Phase Detectors and Balancers" unit which controls the AVC of receiver #2 and the "phase shifter" unit which is the output of receiver #2 (IF output). The display unit which resembles a conventional oscilloscope needs to be amplitude and phase balanced only over the bandwidth of the intermediate

frequency of the receivers. Care is needed here only in that the unit should not overload on signals which are several times as great as required to give full deflection on the scope.

As was explainted previously, the two receiver Watson-Watt is a bidirectional system. The sense is obtained by comparing the phase of the sense antenna with respect to one of the other channels.

Advantages of the Watson-Watt system:

a. Gives a good bearing on a very short pulse transmission.

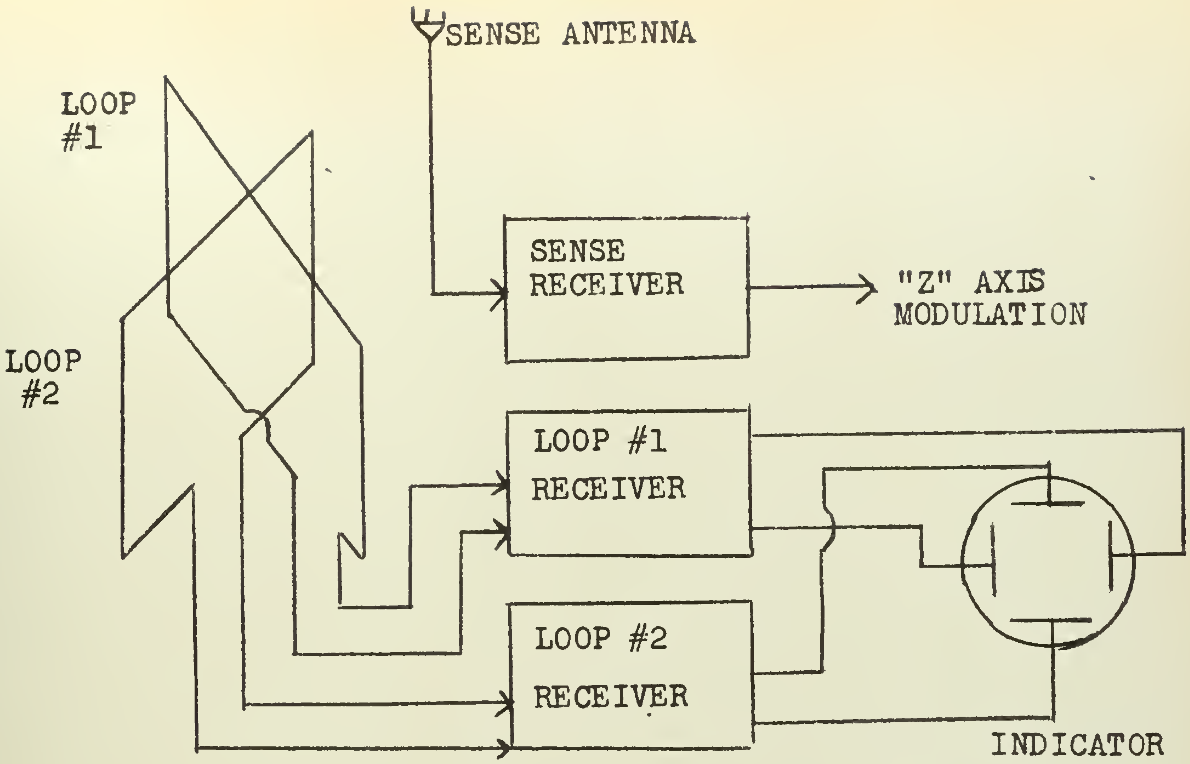
b. It is capable of giving good bearings on a number of stations which are time sharing one frequency.

c. It is capable of giving bearings on two stations which are on the same frequency simultaneously (this gives an oblong pattern on the scope with the bearings of the two signals indicated by the diagonals of the oblong).

Disadvantages of the Watson-Watt system:

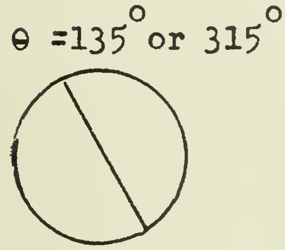
a. It is very complicated in construction which means expense and maintenance problems.

b. The problems of alignment of the receivers increases as the bandwidth of the receivers decreases hence the system may be more subject to noise than the narrow band single receiver systems. It is also difficult to use a variable bandwidth receiver for this type of system.



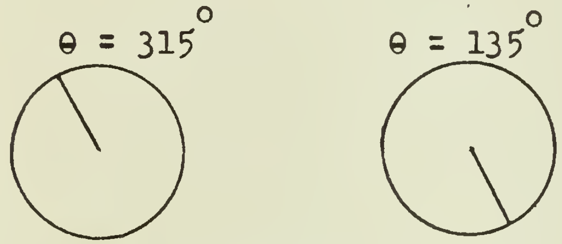
A THREE RECEIVER "WATSON-WATT" SYSTEM

Figure 7.1a



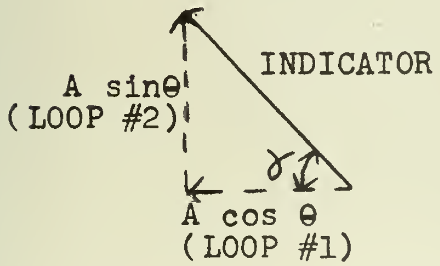
SIGNAL ON INDICATOR WITHOUT SENSE

Figure 7.1b



SIGNAL WITH SENSE ON INDICATOR

Figure 7.1c

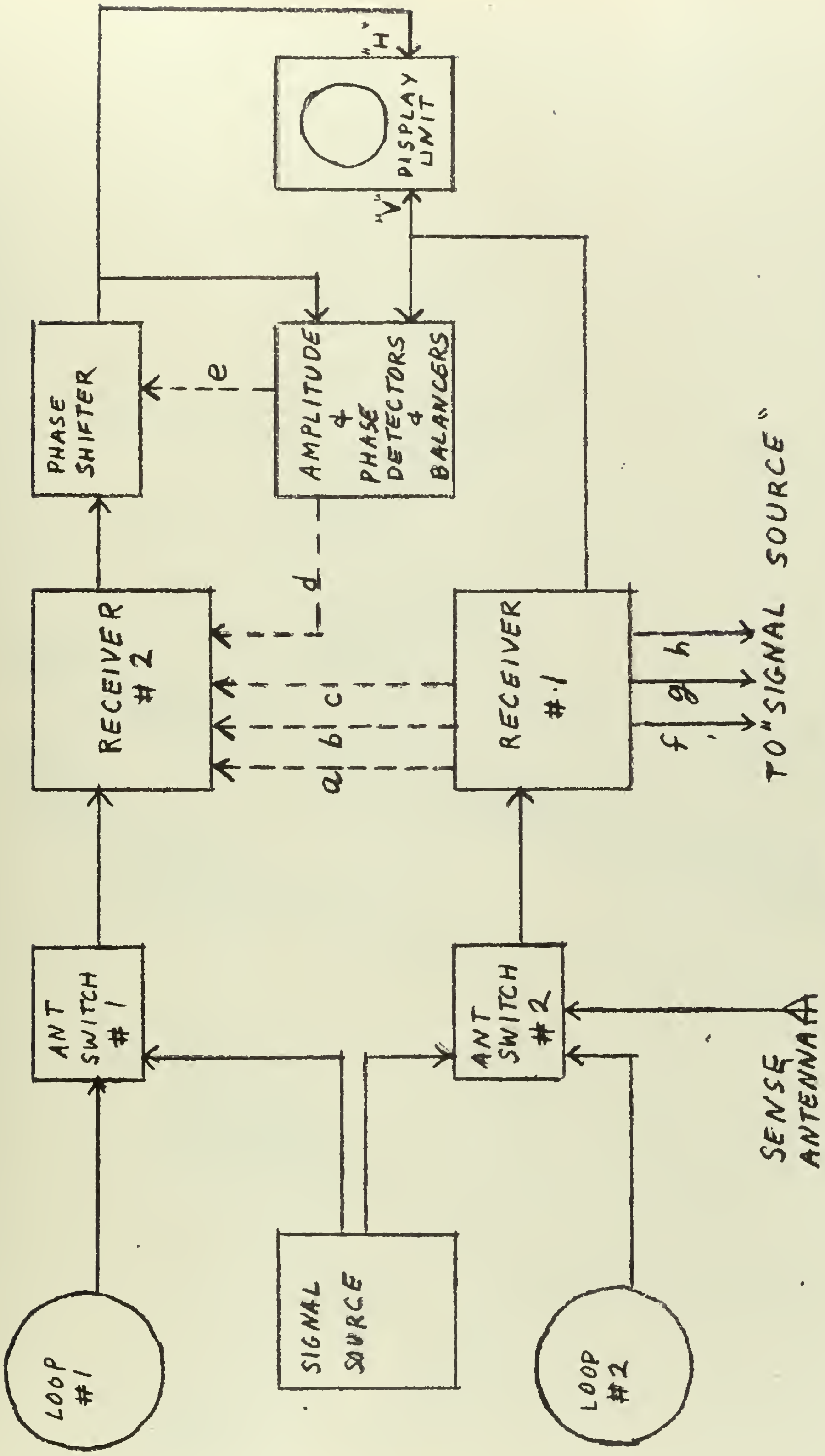


$$\tan \gamma = \frac{A \sin \theta}{A \cos \theta} = \tan \theta$$

$$\gamma = \theta$$

THE "WATSON-WATT" SYSTEM

Figure 7.1



TWO RECEIVER "WATSON-WATT" TYPE DIRECTION FINDER

FIGURE 7.2

Figure 7.2

CHAPTER VIII

POST-RECEIVER DIRECTION FINDER SYSTEMS USING ONE RECEIVER AND THE CROSSED LOOP OR ADCOCK ANTENNA

There have been many ideas as how to accomplish the same thing with one receiver as does the Watson-Watt system with three receivers. This article will deal with the principles involved and then give the block diagrams of several methods as illustrations of these principles.

Figure 8.1 illustrates the principles involved in this type of system. It can be seen that each antenna gives two outputs which are equal in amplitude, but 180 degrees out of phase. Each of the outputs is then combined with the sense antenna output (actually this generally occurs after the "Identifier" in some systems) shifted in phase by 90 degrees such that it is in phase with one of the outputs from each loop. The loop output that the sense antenna is in phase with will depend on the direction of arrival of the signal and it is this situation which permits this system to be uni-directional. The four outputs are then sent to an "Identifier" which "tags" each output and then sends them on to a common receiver. Following amplification in the receiver the signals are sent through a separator and then a detector which in most cases gives a DC voltage proportional to the amplitude of the signal prior to its entering the identifier. Each voltage from the "Detector-Integrators" is applied to its corresponding plate on a cathode ray tube. The action here is one of subtraction (the beam moves due to the difference in potential of the opposite pairs of plates) hence the sense antenna voltage is balanced out (this is the reason that the sense antenna voltage component is left off of this part of the diagram) and the beam moves in the direction in which the sense and loop antenna voltages were in phase. This gives a "dot" indication on the scope for the bearing.

In order to make this dot into a line for easier reading of the bearing some method, such as returning the output of all integrators to zero simultaneously, is used to extend a straight line from the center of the scope to the dot. This is done at some fairly slow rate in comparison to any other sampling rate in the system.

The number of methods by which the signals may be "identified" and separated appears to be numerous. A few methods by which it has been done or appears to be practical to do are listed below:

a. Time separation--The receiver is time shared equally with each of the four signals. This is perhaps the simplest system, but requires a long integration period and relatively stable signals. A simple test in the laboratory indicated that around 17 cps was a fairly good sampling rate. Figure 8.2 is an example of this system.

b. Tone modulation--Each of the four signals is identified by a separate, non-harmonically related tone. All signals are then passed through the receiver together and are separated by tone filters at the other end of the receiver. This system is good in that all of the signals are sent through the receiver simultaneously. It is, however, subject to cross modulation errors and errors from modulation of the carrier prior to its entering the system.

c. Combined time separation and synchronous detection--One signal from each antenna is sent through the receiver at the same time. Each pair of signals from one antenna is time separated. If this time separation rate is asymmetrical for the two pairs

then this can be used for the separation into the four components after the receiver. Figure 8.3 is an example of this system.

d. Time delayed separation--The four signals enter four separate separators simultaneously. The signals are sliced in the separators for a given period of time (t). Each signal, except the first, is then passed through a delay line and then to the receiver. The first separator is fed directly to the receiver. The second separator is fed to a delay line equal to "t". The third separator is fed to a delay line equal to "2t" and the fourth separator is fed to a delay line equal to "3t". The signals are separated at the output of the receiver by a synchronous detector (note that no time delay is needed at this point).

This type system could very nearly provide an instantaneous direction finder resembling the Watson-Watt system since the signal sample is of the same time interval of the signal and no sharply tuned circuits are used for the separation. If the first channel (the one with no time delay) were connected to the receiver at all times except when desiring to "take a bearing", the receiver could be used for search. For pulse type signals the leading edge of a pulse from the receiver could trigger the chopper instead of having the chopper run free (the chopper is the device which time samples the signals at the "Identifier" and provides the timing for the "Separators"). This would permit bearings on several short pulses which were time sharing the same frequency. In this type of direction finder it might be advisable to use a cathode ray memory tube in place of the standard cathode ray tube. Figure 8.4 is a block diagram of this system.

Advantages of the post-receiver direction finder system using one receiver and crossed loops or Adcocks are:

a. The bearing is uni-directional

b. The accuracy of bearings do not depend directly on the sharpness of a null.

c. There are no rotating goniometers or antennas.

d. In the case of the "time delayed separation" system the results obtainable approach the three receiver Watson-Watt system.

e. The systems are fairly simple and provide bearings on fairly short length transmissions provided that the short term variations of the signals are not too great, otherwise a long integration time is required for accurate results on all systems except the "time delayed separation" system.

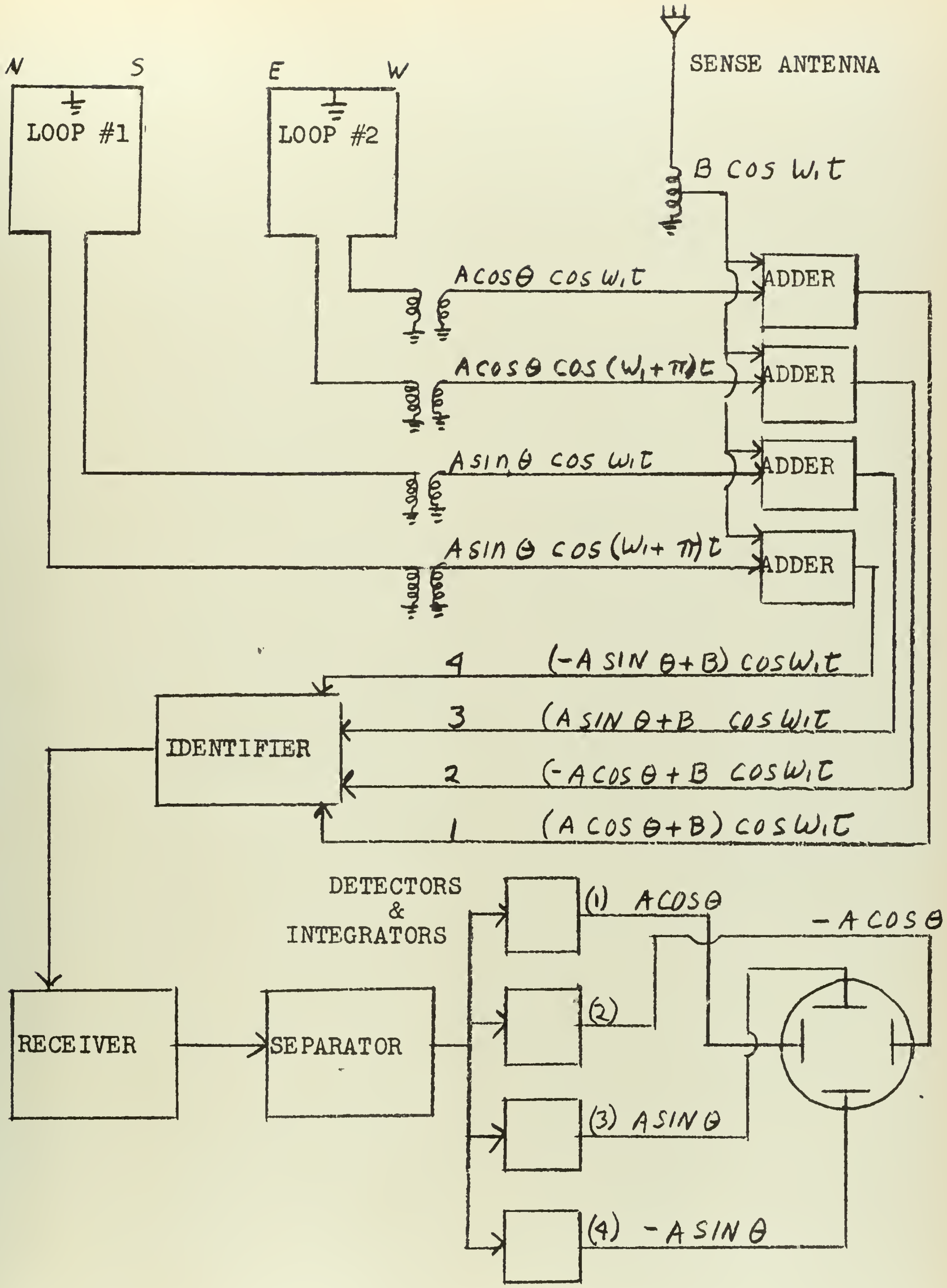
Disadvantages of this system are:

a. Noise is generally added to the system prior to the receiver by the "tagging" technique employed. This causes a degradation of the signal to noise ratio over that obtainable by the Watson-Watt system.

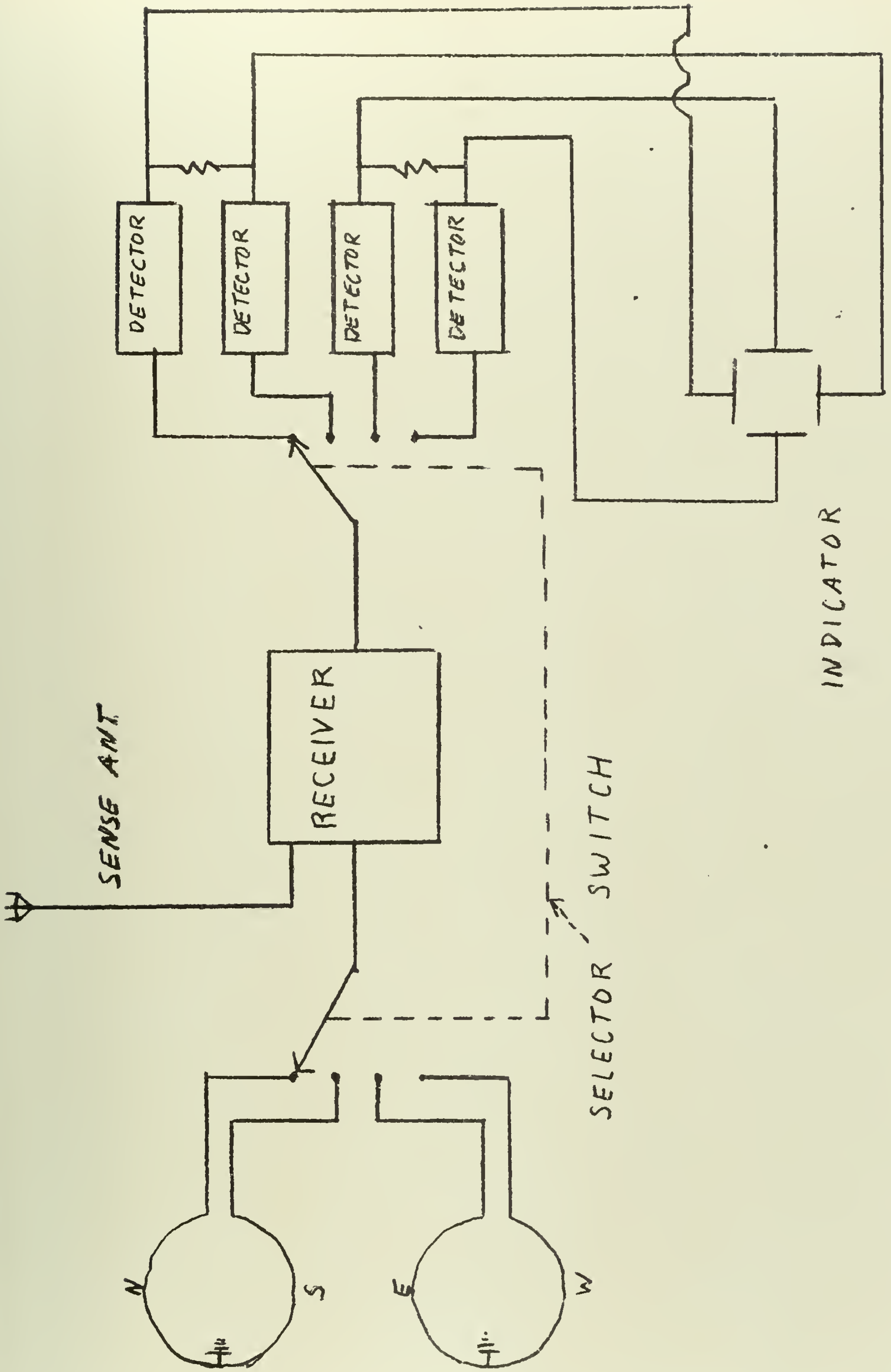
b. It is susceptible to error from the pulse repetition frequency and amplitude modulation of the signal except in the "time delayed separation system".

c. The output signal from the receiver is distorted.

d. There is a good chance for cross modulation products if a strong signal is present at the antenna.

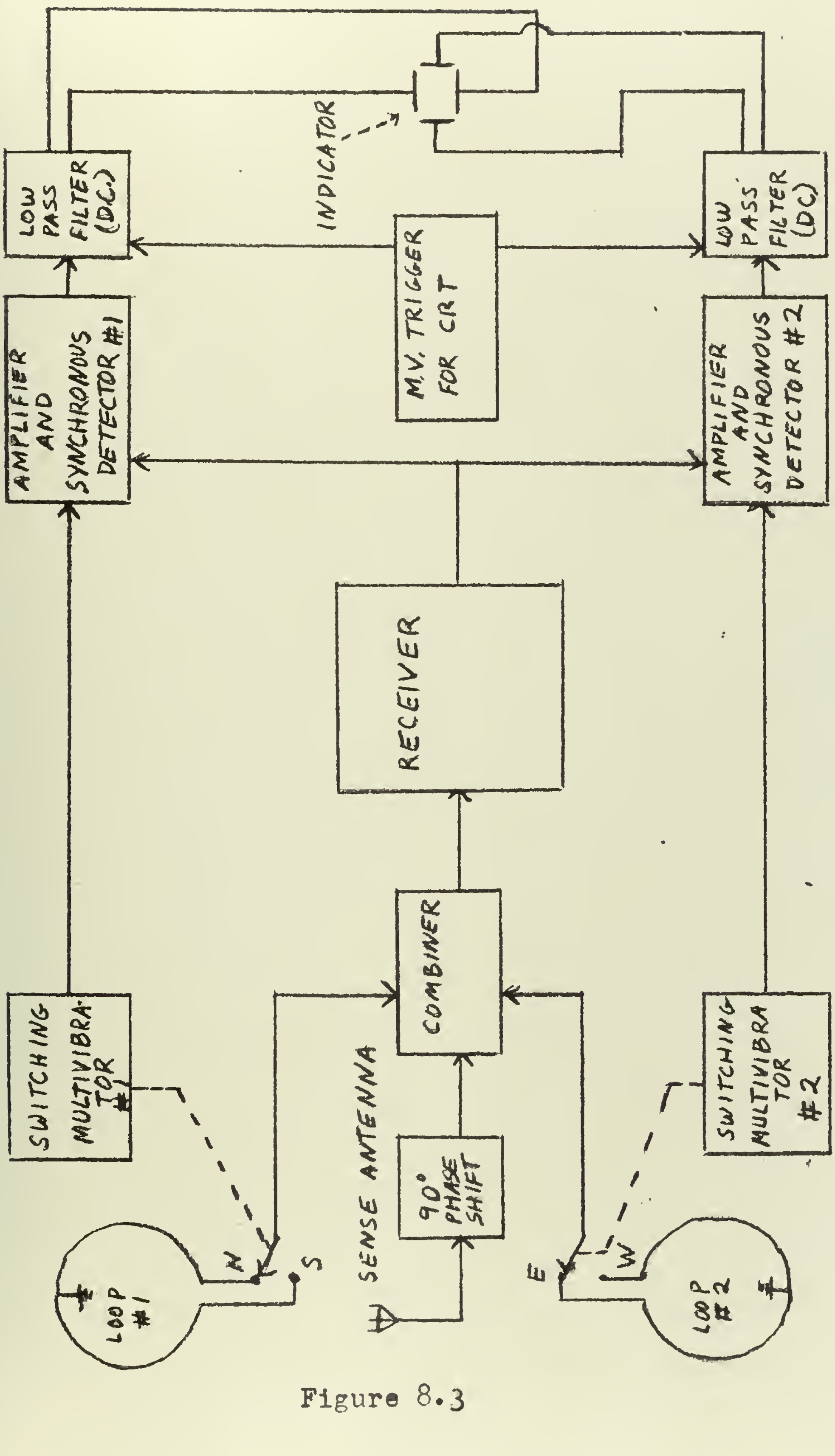


A POST RECEIVER DIRECTION FINDER USING ONE RECEIVER
Figure 8.1



A POST RECEIVER DIRECTION FINDER SYSTEM (1)

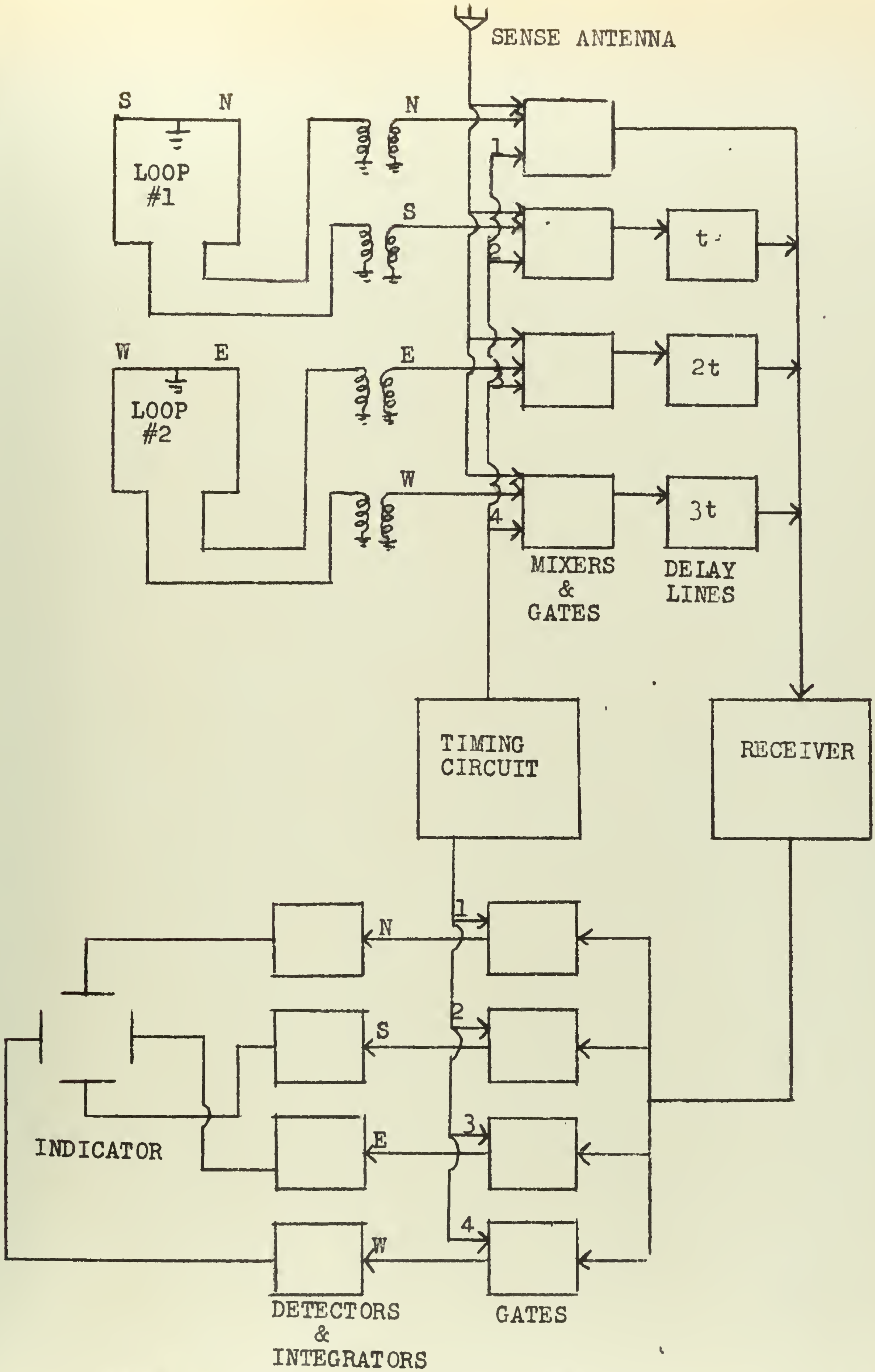
Figure 8.2



A POST RECEIVER DIRECTION FINDER SYSTEM (2)

Figure 8.3

Figure 8.3



SINGLE RECEIVER, POST RECEIVER TIME DELAYED SEPARATION SYSTEM

Figure 8.4

CHAPTER IX

THE DOPPLER DIRECTION FINDER SYSTEM

The doppler direction finder system provides a unique method of obtaining an uni-directional bearing on a radio signal. The method is relatively free of multipath and siting errors. Its difficulty, in the frequency range under consideration, is the size required for the antenna installation.

The doppler direction finder works on the principle that if the antenna is moved towards a signal the apparent frequency is increased and if it is moved away from the signal then the apparent frequency is decreased. The amount of change in frequency is proportional to the speed of the antenna with reference to the path of propagation of the radio waves. The net effect of the rapidly rotating antenna is to produce a frequency modulation of the carrier with the amount of frequency deviation dependent on the speed of the antenna and the frequency of deviation dependent on the speed of rotation of the antenna (see Figure 9.1). This frequency modulation can then be detected and compared with the rotational position of the antenna to compute the direction of arrival of the signal.

Figure 9.2 shows a block diagram of a very simple doppler direction finder system. The commutator effectively rotates the antenna at high speeds. The motor drive for the commutator is also coupled to a device which gives a sine wave output whose frequency corresponds to the rotational frequency of the commutator and whose phase corresponds to the instantaneous position of the commutator. The receiver is a normal receiver of the narrow band FM type. The limiters remove all amplitude modulation from the signal and the discriminator recovers the frequency

modulation component of the signal. The amplifier amplifies this frequency modulation component (now an audio frequency) and the bandpass filter permits only the frequency corresponding to the antenna rotational frequency to pass. The phase difference measuring device compares the phase of the sine output from the motor drive (antenna position) to that of the discriminator output. The phase difference gives an uni-directional angle of arrival of the incoming wave.

The system shown in Figure 9.2 has one major disadvantage. The system is subject to error due to any frequency shift within the signal or phase shift caused by multipath which has a component of frequency shift near that of the rotational speed of the antenna. This may be nearly eliminated by several methods. One method would be to compare the output of the antenna commutator with that from a fixed antenna. The output would then be the difference between the true signal and the commutated signal with differences due to undesired frequency modulation of the signal being removed.

Equation 9.1 gives the theoretical peak frequency deviation for a given system. The actual deviation is larger than this and depends on the number of antennas used and the system of commutation. In a simple system such as shown in Figure 9.2, if the number of antennas is twice the value given by equation 9.2, then the deviation will approach this theoretical value to a fair degree. Equation 9.2 gives the minimum number of antennas for the system shown in Figure 9.2 to limit the maximum phase difference between antennas to 180 degrees. There is some possibility that the antennas will be purposely widely spaced in order to obtain a higher peak frequency shift for any given rotational speed and antenna radius.

The selection of the diameter of the antenna circle to one wave length or more would be very desirable. This is nearly impossible in the frequency range under consideration.

The selection of the rotational speed should be based on what would give a reasonable doppler shift (frequency shift to remain within the bandwidth of the receiver) and would scan rapidly enough to obtain at least one rotation per the shortest pulse anticipated.

The recovery of bearings on short pulses could be enhanced by the incorporation of a memory device in the system. This memory could be placed at a high level post detection point and hence would have no serious effect on the signal to noise ratio of the system.

Further information on the doppler systems is contained in references (18) and (22) of the bibliography.

Advantages of the doppler system:

a. Minimum error due to sky wave or siting (possible with proper design).

b. Uni-directional bearings are possible.

c. Works on a high level signal.

d. Works on fairly short signals (especially with the memory).

e. Fairly simple in design for easy maintenance.

f. Simple to operate.

Disadvantages of the doppler system:

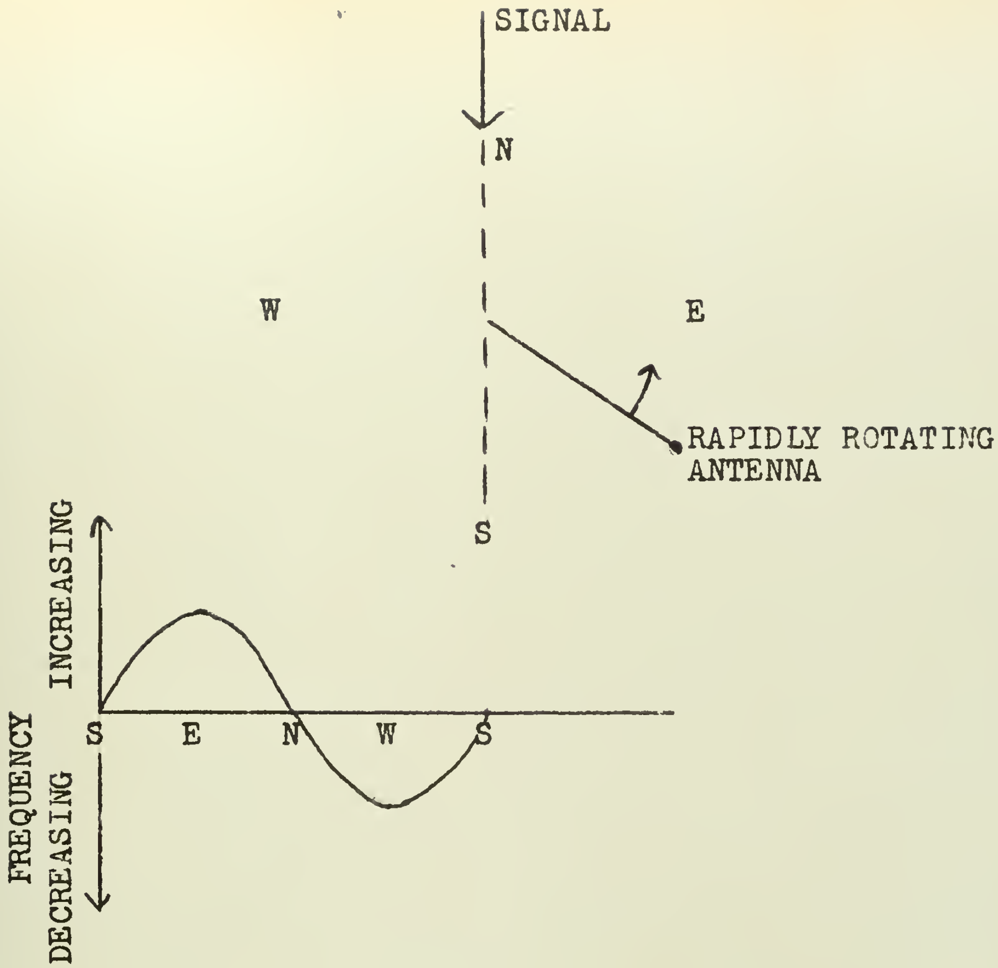
a. Requires considerable space.

b. Requires a large number of antennas and matched cables.

c. Frequency deviation peaks (theoretical) depends directly on the frequency of the incoming signal and hence this system may not cover the band from 10-550 kc/s on one antenna system or one rotational speed.

d. Practical frequency deviations obtainable for the lower frequencies would probably be very small.

e. Subject to errors from frequency modulation of the signal prior to reception unless special means are employed to remove this effect.



$$f_d = \frac{2\pi r \quad f_r}{\lambda}$$ Equation 9.1

$$A_m = \frac{4\pi r}{\lambda}$$ Equation 9.2

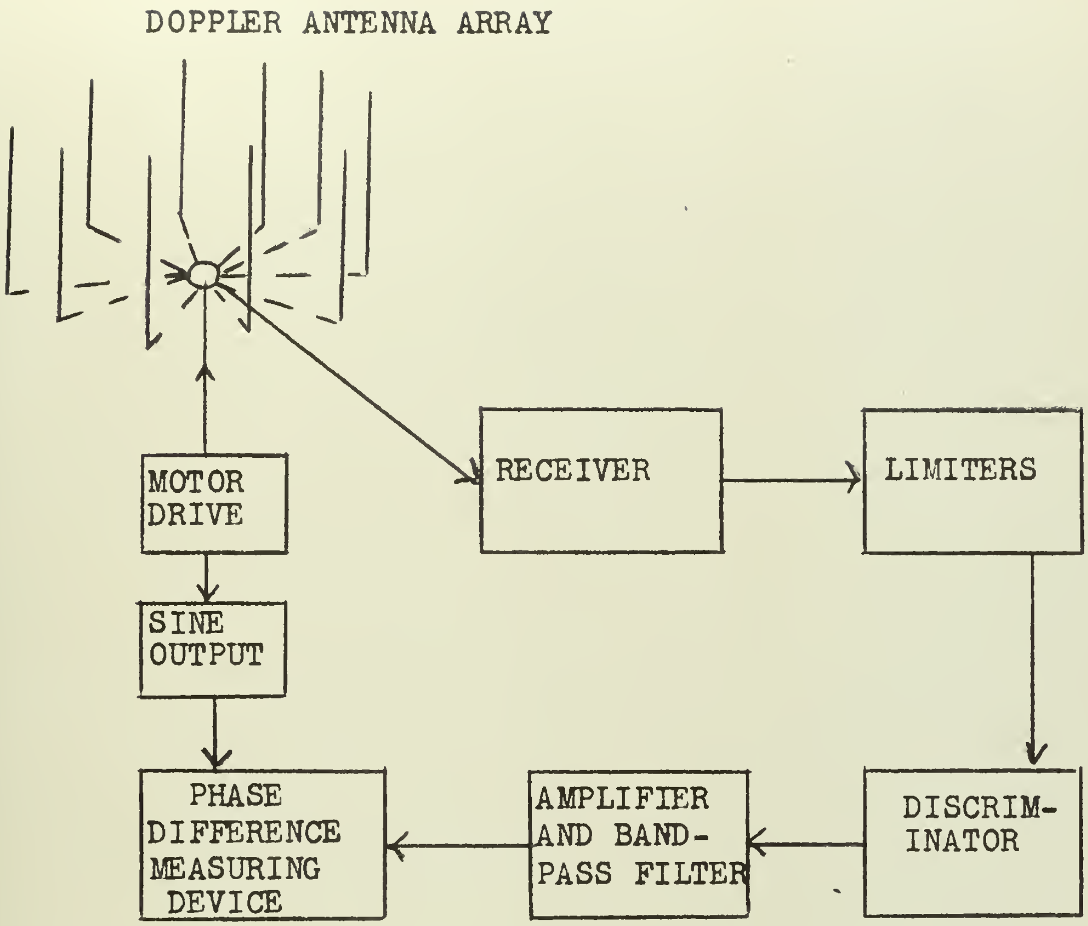
$f_d \stackrel{d}{=}$ Peak frequency deviation if an infinite number of antennas were used

$f_r \stackrel{d}{=}$ The frequency of rotation of the antenna

$A_m \stackrel{d}{=}$ The minimum number of antennas for a maximum $\frac{\pi}{2}$ radians phase shift between antennas

DOPPLER EFFECT

Figure 9.1



A DOPPLER DIRECTION FINDER SYSTEM

Figure 9.2

CHAPTER X

TIME DIFFERENCE DIRECTION FINDING

Time difference (or phase difference) direction finding utilizes the time difference of arrival of the same signal at two separate points to determine the bearing or line of position. Uni-directional antennas may be used, and amplitude differences contribute little error. The reason for the preference of the name "time difference" over "phase difference" is that time difference is independent of frequency whereas phase difference measurements are dependent on frequency.

Figure 2.2 shows the basic principles of time difference direction finding. Equation 10.1 shows that the time difference is dependent only on the angle of arrival and the separation of the antennas. Figure 10.2 shows the time difference in micro-seconds vs. bearing for a one mile separation of the antennas. Equation 10.2 shows that the phase difference in radians depends on the angle of arrival, spacing of antennas, and the wave length of the signal. Equation 10.3 gives the incremental change in phase difference for an incremental change in the angle of arrival. This is essentially an error equation. From this equation it can be seen that the accuracy of an equipment which measures phase (or which balances time against a phase match) will be more accurate for angles of arrival near 90 degrees than it will be for angles of arrival near zero degrees, other conditions being equal. Figure 10.3 shows the incremental time difference error equivalent to a one degree error in bearing vs. bearing for a one mile separation of the antennas. It may be seen that when the angle of arrival is less than about 30 degrees, the accuracy capability falls off rapidly, hence it would be recommended that two pair of antennas at right angles to each other be used in order that

the angle of arrival would always be greater than 45 degrees. This arrangement has another advantage in that it removes the ambiguity that exists with only one pair of antennas. The two pairs of antennas could also be used to check each other for any source of error in the system.

Figure 10.1a shows a block diagram of a single receiver system using time delay. The fixed delay in the left antenna lead insures that the variable time delay will work with realizable values over the entire 360 degrees. The adder combines the two antenna signals linearly (no cross products) and feeds the signal to a single receiver. The variable time delay is then adjusted for a minimum signal output from the receiver. The variable time delay may be calibrated directly in degrees.

The major source of trouble in this system is the horizontal pickup of the transmission lines. This system is especially sensitive to this because the transmission lines must be very long to obtain a practical accuracy and the system operates on a signal null which is affected very seriously by even a small amount of vertical pickup. It is doubtful with presently known techniques that this system will be practical.

Figure 10.1b is a block diagram of a twin receiver system. The time difference indicator might be a phase difference indicator in which case the "time delays" shown would not be necessary since the bearing could be computed from the phase difference and the frequency (signal frequency, not the receiver intermediate frequency). If the time difference indicator is actually a device for obtaining a good phase balance then the variable time delay may be varied for the phase balance and the direction read directly off of the variable time delay.

This system is also subjected to error due to pickup in the horizontal transmission lines, but the errors should be reduced over the

single receiver system since the receivers operate on the full signal from a vertical antenna and not on a difference signal,which should also permit better operation under conditions of low signal to noise ratios.

The receiver system is nearly the same as that for the Watson-Watt direction finder except that amplitude stability is not required. The time-difference system does require a higher degree of phase stability than does the Watson-Watt system.

The two receiver time difference system lends itself to a very long base line by the use of micro wave relay links rather than physical transmission lines. Reference (23) is a recent German report (in English) on some successful work with micro wave links on signals in the frequency range under consideration in this paper. The long base lines, while potentially more accurate than the short base line systems, also has more ambiguities than the short base line system.

Advantages of the twin receiver time difference direction finder:

a. Potentially very accurate.

b. Good sensitivity (antennas can have a greater gain than can practical Adcock and loop antenna systems).

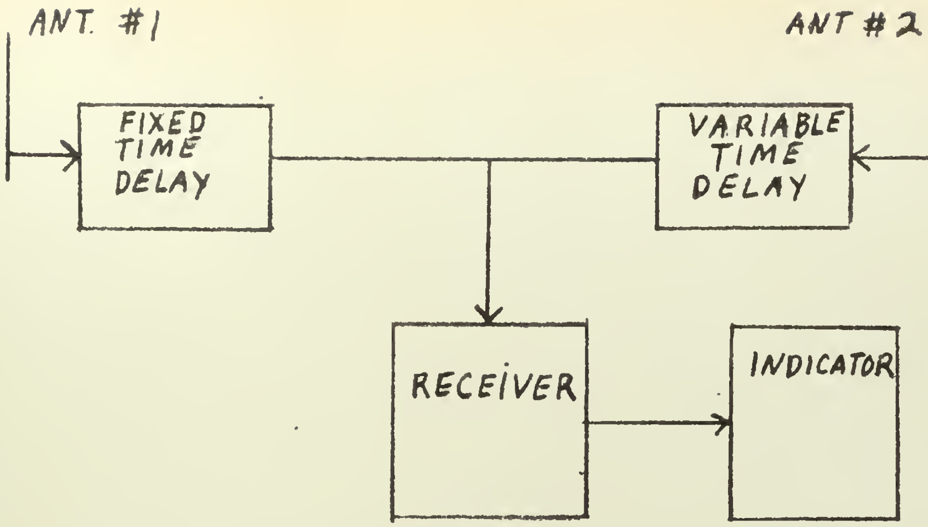
c. Adaptable to use on short pulse systems and time shared frequencies by certain modifications.

The disadvantages of the twin receiver time difference system:

a. It is a very difficult engineering problem (balanced receivers and minimum phase distortion or shift in transmission lines or relay links).

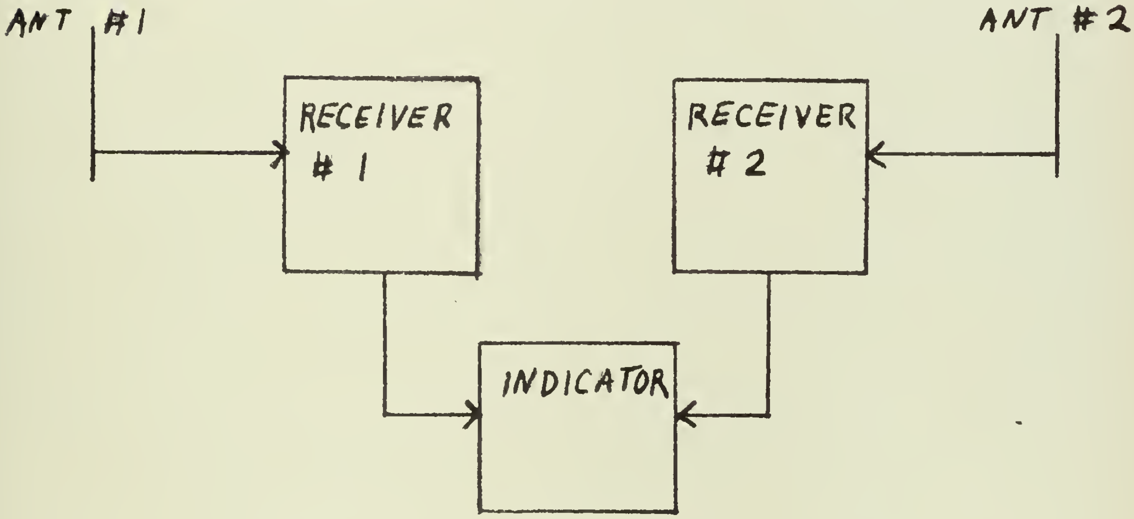
b. Probably very expensive and difficult to maintain for the above reason.

c. Requires considerable space (the space between antennas however may be used for other purposes).



A SINGLE RECEIVER TIME DIFFERENCE DIRECTION FINDER

Figure 10.1a

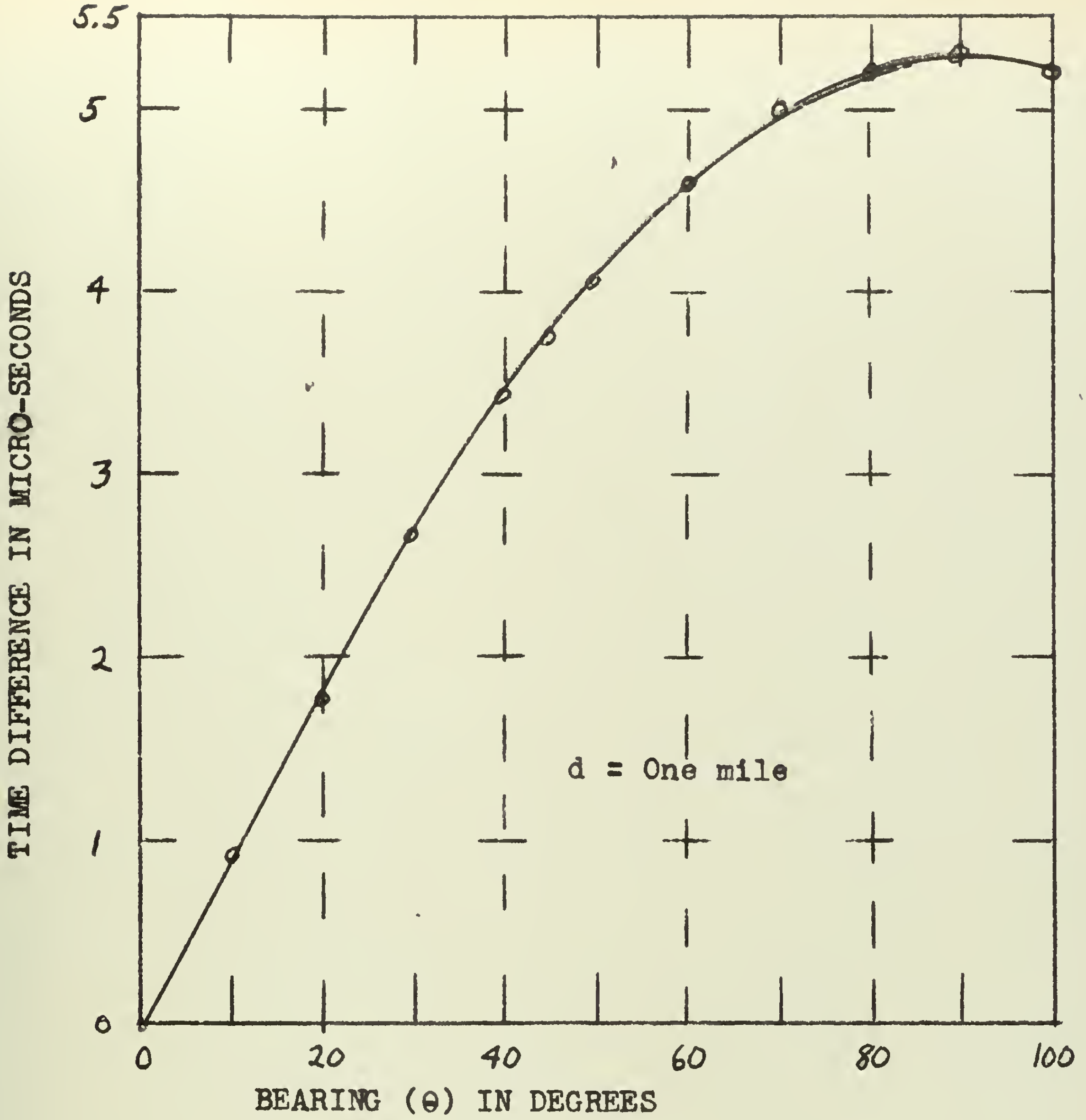


A DUAL RECEIVER TIME DIFFERENCE DIRECTION FINDER

Figure 10.1b

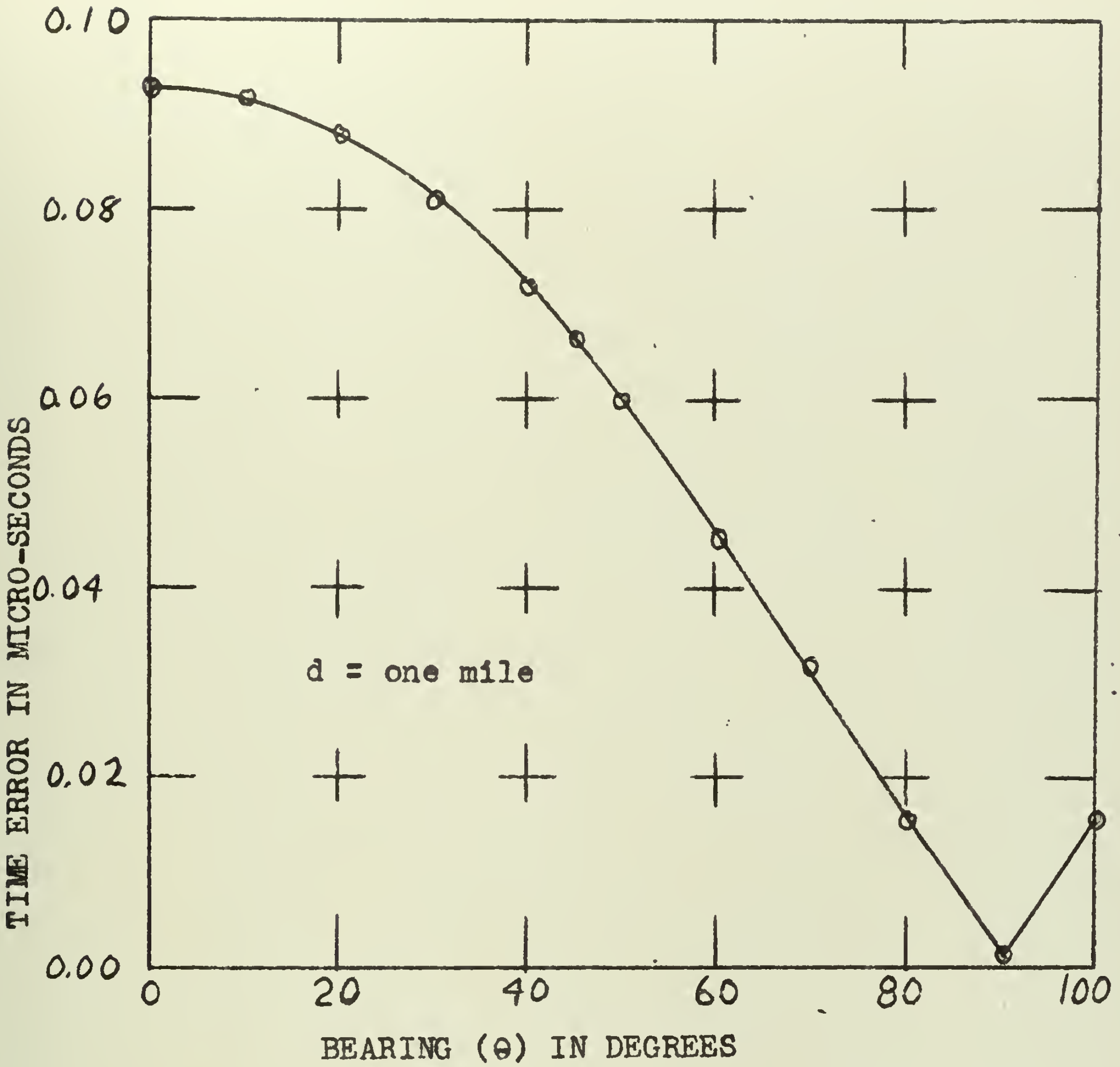
TIME DIFFERENCE DIRECTION FINDERS

Figure 10.1



TIME DIFFERENCE VS BEARING

Figure 10.2



TIME DIFFERENCE ACCURACY VS BEARING REQUIRED FOR
A ONE DEGREE ERROR IN BEARING

Figure 10.3

CHAPTER XI

SELECTION OF A RADIO DIRECTION FINDER SYSTEM

11.1 Selecting a Direction Finder System Given the Requirements.

One of the ultimate aims of this paper is to provide a method by which the best system may be selected for any given set of conditions. The conditions (requirements) of the system must be carefully set up by both operational and technical personnel to be of any true value. Too often the requirements are made up by a few individuals who are not fully informed on all the points involved and the results are either a system that works well when an engineer operates and maintains it or a system that does not require much skill or maintenance, but does not do the entire job. Listed below are some of the conditions which might be the determing factors in selecting a direction finder system:

a. Frequency range

b. Site requirements

   1. Small--readily portable

   2. Medium--semi portable

   3. Large--fixed station

c. Required degree of accuracy

   1. Ground wave

   2. Sky wave or combination of ground and sky waves

d. Types of signals to be received

   1. Signals on for long periods of time

   2. Signals of a short, repetitive nature

   3. Short signals, not repetitive

   4. Signals time shared with the time sharing period being relatively short (otherwise "1" above covers)

e. Cost

f. Ease of operation

g. Reliability

h. Maintenance

i. Adaptability to automatic operation

j. Is the system inherently uni-directional

This chapter will not cover all of the possible methods of obtaining a line of position as described in Chapter 2. Only those types which appear at the present time to be practical as the primary means of direction finding are included here. These direction finder systems are:

A. Simple manual single loop (may be remotely controlled)

B. Motor driven single loop with visual display

C. Automatic direction finder (single loop, servo driven)

D. Parallel loop

E. Crossed loop Watson-Watt three receivers

F. Crossed loop single receiver, post-receiver direction finding

G. Crossed loop with goniometer (visual system with manual capabilities)

H. Adcock antenna with goniometer (visual display with manual capabilities)

I. Adcock three receiver Watson-Watt

J. Adcock single receiver, post-receiver direction finding

K. Two receiver time difference

L. Doppler

In regards to figure 11.1, the following code is used for the comparison:

"Y" means that the system may meet the requirement on a "Yes" or "No" basis.

"N" means that the system probably can not meet the requirement on a "Yes" or "No" basis.

"1" best--meets the requirements such as "most accurate", "least expensive", "receives the shortest pulse signals", etc.

"2" good--not quite as good as "1" above, but still very satisfactory.

"3" fair--not as good as "2", but passable.

"4" poor--may meet requirement, but not normally recommended.

"5" least likely to meet requirements.

"H" best suited for the higher end of the frequency band under consideration.

"B" suited for any frequency range in the 10-550 kc/s band.

The grading of the systems on Figure 11.1 are those of the author based on currently available techniques. There is still considerable room for improvement on some of these systems and some of the "grades" may be radically changed.

11.2 Example of the Selection of a Small, Portable Direction Finder System.

The following will illustrate the method of choosing a direction finder system based on the following specifications:

a. Must be capable of installation in a small van including antennas and power.

b. Frequency range 10-550 kc/s.

c. Operation on CW and phone signals.

d. Ease of operation and maintenance.

DIRECTION FINDER SYSTEM

FACTORS AFFECTING THE SELECTION OF A D/F SYSTEM

	A	B	C	D	E	F	G	H	I	J	K	L
a	B	B	B	H	B	B	B	H	H	H	B	H
b1	Y	Y	Y	N	N	Y	Y	N	N	N	N	N
b2	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N	N
b3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
c1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
c2	N	N	N	Y	N	N	N	Y	Y	Y	Y	Y
d1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
d2	3	2	4	3	1	3	2	2	1	3	3	2
d3	5	2	5	5	1	3	2	2	1	3	3	3
d4	4	4	5	4	1	4	4	4	1	4	4	5
e	1	2	2	3	5	2	2	3	5	2	5	4
f	3	2	1	4	2	1	2	2	2	1	3	2
g	1	2	2	1	4	3	2	2	4	3	3	2
h	1	2	2	1	4	3	2	2	4	3	3	3
i	5	4	1	5	3	3	4	4	3	3	3	4
j	N	N	Y	N	Y	Y	N	N	Y	Y	N	Y

SUMMARY OF DIRECTION FINDER SYSTEM CHARACTERISTICS

Figure 11.1

e. High reliability.

f. Should not have ambiguous bearings.

The following systems (listed by letters of the alphabet as described in article 11.1) will meet each specification as listed above:

Specification	Systems that meet specification	Remarks
a.	A, B, C, F, G	Loop Systems
b.	A, B, C, E, F, G, K	
c.	ALL SYSTEMS	
d.	A, B, C, G, H	
e.	A, D, B, C, G, H	Order of preference
f.	C, E, F, I, J, L	

From the above it can be seen that type "C" (single loop, automatic direction finder) is the system that would be most likely to best meet the requirements. Type "F" (crossed loop, single receiver, post-receiver direction finder) would also be considered even though it is more complicated. Type "B" is eliminated because it is not inherently uni-directional.

11.3 Example of the Selection of a Fixed Station Direction Finder System.

The following is an analysis of the selection of a direction finder system to meet the following requirements:

a. Installation to be of a permanent nature.

b. A maximum of one degree error desired on all signals.

c. Must be useful against ground and sky waves.

d. Maximum sensitivity and selectivity.

e. Should be useful against all types of emissions.

f. Must be capable of operation by relatively untrained operators.

g. High reliability desired.

h. Automatic reporting capability is desired.

i. Frequency calibration must be accurate to within 20 cps over the entire band.

j. Frequency range of 10-550 kc/s.

(note: the objective of this system is that it is to provide the best equipment available with cost only a minor consideration. It may be necessary to use more than one antenna array or even more than one basic system to accomplish the desired task).

The loop antenna systems A, B, C, D, E, F, and G are eliminated at the outset due to the susceptibility to sky wave error (except "D" which is not sensitive enough to meet the requirements in this frequency range).

In regards to Adcock systems the frequency range for any one Adcock array ordinarily would not exceed a three to one ratio. This would mean that four arrays would be required to cover the 10-550 kc/s range. Three arrays could be used if a 3.8 to 1 ratio were used and two arrays could be used if a 7.4 to 1 ratio were used. The latter may be considered as unacceptable hence the 3.8:1 seems the most practical. The low frequency Adcock would then cover the 10-38 kc/s range and would have a diagonal distance of 1,578 meters or nearly one mile when using one-fifth wave length as the maximum spacing for a one degree error. This size array is probably not very practical as the horizontal pickup would probably be too great. The next Adcock would cover the range from 38-145 kc/s with a diagonal spacing of 413 meters which is within the realm of practicability, but still a very difficult problem. The next array would cover the frequency range of 145-550 kc/s and would have a

diagonal distance of 109 meters which is a practical size antenna array. The conclusion from this paragraph is that an Adcock type system should not be used below, say, 145 kc/s if another system is available.

In regards to the Doppler system if we assume a maximum rotational rate of 30 cps and a minimum frequency shift of 25 cps then the antenna radius of the Doppler array must be approximately 4000 meters computed at 10 kc/s and would be approximately 73 meters computed at 550 kc/s. It appears that the Doppler would not be satisfactory with its present state of development at the lower frequencies. The Doppler system is also at a disadvantage in that it will not work very well on very short transmissions or on time shared transmissions where the shift rate between transmitters is relatively high.

The "Time Difference" direction finder has a sensitivity which can be made independent of frequency since the antenna spacing has nothing to do with the sensitivity in this system. If we assume a short base system (one in which the antenna spacing never exceeds one wave length) then the pair spacing for the time difference antennas for the same three frequency bands as was computed for the Adcock antennas are:

a. 10-38 kc/s is 7,890 km or a little less than five miles.

b. 38-145 kc/s is 2,065 km or approximately 1.3 miles.

c. 145-550 kc/s is 545 km or less than a third of a mile.

These antenna systems are practical although the method of transmitting the information from the antenna to the receiver is of the utmost importance. Standard cables may not be suited for this due to pickup and the change of velocity in the cables with changes in temperature. It might be necessary to go to micro-wave relays similar in type to the system now operating in Germany. One set of antennas could be used for

the entire 10-550 kc/s. The smaller separation above (545 km) would give unambiguous answers for two sets of antennas at right angles, but would not provide full accuracy on the lower frequencies. The widest spacing above (7,890 km) would provide the best accuracy, but would suffer from many ambiguities at the higher frequencies.

In regards to the other specifications the time difference direction finder can be made adaptable. It is not appreciably affected by sky wave. It probably can be made easy to operate. The most difficult specification to meet will be that it must operate against all types of emission. The short, time shared pulse transmission would provide some engineering problems in circuitry and display. It is the belief of the author that these problems can be solved.

It should be mentioned here that unambiguous bearings may be obtained on very short signals by simultaneous comparison of measurements from two sets of two antennas each spaced at right angles or from one set of three antennas arranged in a triangle. This latter arrangement would probably be the best for simplicity of equipment.

The author has arranged below, in the order of desirability, those systems which might best meet the needs of a fixed station direction finder in accordance with his opinion:

1. Time Difference Direction Finder.
2. Loop Watson-Watt system 10-150 kc/s

   Adcock Watson-Watt system 150-550 kc/s.
3. Loop, single receiver, post-receiver system using time delay for 10-150 kc/s

   Adcock, single receiver, post-receiver system using time delay for 150-550 kc/s.

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APPENDIX I

LOW AND VERY LOW FREQUENCY PROPAGATION EQUATIONS

1. Ground Wave Propagation. (Norton's Equation)

$$\bar{E} = \frac{6.14 \sqrt{Pr} \quad A_1}{D}$$

Pr = Radiated Power
D = Distance from transmitter to receiver
A_1 = Attenuation factor (a function of "p" and "b")

$$p = \frac{1.77 \times 10^{-18} \; f_{kc} \; D \; \cos \; b}{\sigma_{emu} \; \lambda}$$

$$b = \tan^{-1}(5.55 \times 10^{-19} \; \frac{e + 1}{\sigma_{emu}} \; f_{kc}) \text{ radians}$$

e = dielectric constant of earth
σ = conductivity in emu of earth

For a more detailed work, see K. A. Norton's article "The Calculation of Ground Wave Field Intensity over a Finite Conducting Spherical Earth" in IRE December 1941.

2. Sky Wave Propagation.

$$\bar{E} = \frac{2 \; \bar{E}_o \; \psi}{D} \; \cos^2 \left(\text{arc} \; \tan \frac{2h}{D}\right)$$

ψ = Reflection coefficient at E layer
D = Distance between transmitter and receiver
h = effective (apparent) reflection height
$\bar{E}_o$ = Field strength radiated by the transmitter at a unit distance

For further information see "Proceedings of the IEE" Part IIIA, Number 52, March 1951, page 81.

3. Combined Ground and Sky Wave Propagation. (Austin-Cohen Equation)

$$\bar{E} = \frac{298 \quad 10^3 \sqrt{Pr}}{D} \sqrt{\frac{\theta}{\sin \theta}} \qquad e^{-aD/\lambda}$$

(Note: This equation basically for the VLF range)

$\overline{E}$ = received field intensity in microvolts per meter
Pr = radiated power from antenna in kilowatts
D = distance in kilometers between transmitter and receiver
θ = Transmission distance in radians (angle subtended between transmitter and receiver measured from the center of the earth)
e = 2.718
λ = wavelength of radiation in kilometers
a = attenuation constant

For further information, see "Reference Data for Radio Engineers" Fourth Edition, page 711, IT&T.